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Study of voltage, acid concentration, and temperature on nanopore structures

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STUDY OF VOLTAGE, ACID CONCENTRATION, AND TEMPERATURE ON NANOPORE STRUCTURES

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ABSTRACT

STUDY OF VOLTAGE, ACID CONCENTRATION, AND TEMPERATURE ON NANOPORE STRUCTURES

By Rajvinder S. Virk

Anodization of aluminum is a relatively well-known technique which dates back several decades. Under appropriate conditions, this electrochemical process produces nanopores on an aluminum surface. Despite past efforts, the effects of acid electrolyte solution concentrations and intensity of voltage on nanopore characteristics has not been reported in detail in literature. In this study, a 500 nanometer (nm) aluminum film is sputtered upon a prepared silicon substrate, containing a 250 nm titanium sub-layer. This substrate is electrochemically anodized, chemically etched, and then re-anodized in the presence of oxalic and phosphoric acid solutions. The effect of simultaneously varying voltage intensity and the oxalic and phosphoric electrolyte concentrations was explored by utilizing a design of experiment technique. A subsequent temperature and grain size study was also conducted. The effect of modifying these parameters was determined by calculating the change in pore diameter, nanopore density, and a tortuosity values. It was found that voltage has the greatest effect on influencing the pore density (a decrease of 1.01 E+10 pores/cm^2), diameter (an increase of 15.42 nm), and tortuosity (an increase of 13.58 %).

AKNOWLEDGEMENTS

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For their inspiration, constant encouragement, and understanding I owe a great deal of appreciation to my grandparents, parents, and family. Without them this process would not have come to fruition.

Finally, I would like to thank my wife Karamjit, for her invariable encouragement, constant support, and devotion. I would like to thank her for being resolute and sympathetic to the process of my professional development, for tolerating my atypical work and school schedule, and for simply being a pillar of strength when I needed her most. To her and our unborn child I dedicate this thesis.

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1.0 INTRODUCTION

1.1 General Background

Technology is prevalent in almost every aspect of our daily lives. From the moment we wake to the moment we sleep, now more than ever, we all share a symbiotic relationship with technology. Dating to the beginning of the industrial revolution to the present, the drive and actualization of producing technological advancements faster, better, and cheaper has essentially influenced technology itself. This is best illustrated by the law of the S-curve. The law of the S-curve states that advancements in science and technology come about twice a century and lead to massive wealth and technological changes. The law of the S-curve is shown in Figure 1. As exemplified by this curve nanotechnology may be the next revolutionary force to change science and technology.

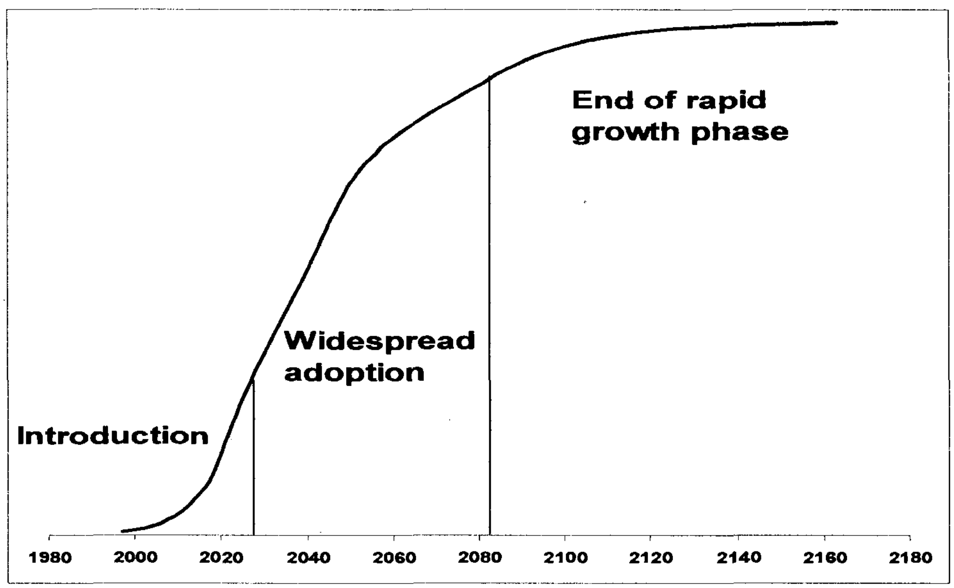


Figure 1. The Law of the S-Curve.

An excellent example of this evolutionary technological process is the integrated circuit. They are employed in, but not limited to, computers, cellular phones, audio and media devices, automobiles, major appliances, and almost every type of communication technology.

The size of the devices which utilize semiconductors has decreased in almost a linear relationship with the size reduction of the semiconductors themselves. Since the invention of the first integrated circuit in the 1960's, the density of the devices incorporated on the substrates has been increasing dramatically [1]. By the mid 1970's the substrates contained over 100,000 devices per chip and by 2000 this number had exceeded the 1 billion mark [1]. The perpetual desire to increase the number of devices and decrease the size of the substrate has driven the semiconductor industry for decades. A new technology is emerging that will not only sustain this path of progression, but dramatically accelerate it.

1.2 Nanotechnology

Current semiconductor technology and practices enable the creation of nanodevices (incorporating two-dimensional (2-D) and some one-dimensional (1-D) confinements), albeit at a high cost and with significant technological limitations. To accomplish the daunting task of semiconductors on a nanoscale level, nanotechnology is the next step of the evolution. Richard Feynman gave a famous talk ("There's Plenty of Room at the Bottom") on December 29, 1959, at the annual meeting of the American Physical Society at the California Institute for Technology that is recognized as giving birth to nanotechnology [2]. From that talk, Feynman's visualizations are presented and the Feynman Prize was established to support researchers in their pursuit of his vision. In

1991 S. Iijima [3] discovered carbon nanotubes; the discovery stimulated much interest due to the unique mechanical and electrical properties [4, 5]. Since this discovery many nanostructures have been discovered.

Nanotechnology is defined as a technology where the dimensions and tolerances are typically in the range of 0.1 nanometers to 100 nanometers [6]. Nanostructures are classified as 0, 1 and 2 dimensional. Zero-dimensional included nanodots and nanoparticles, 1-dimensional included nanobelts, nanowires, nanorods and nanotubes, 2-dimensional structures include quantum wells, super lattices and ultra thin films. . Applications of these effective devices are expected to have almost unlimited potential in all scientific fields. Some of the current areas of research include biotechnology, micro-gears, space technology, pharmaceuticals, solar cells, and biomolecules.

Of these structures one-dimensional nanowires are of great interest due to their unique properties and feasible application in semiconductors and nanoelectronics. One-dimensional structures allow for efficient transport of electrons, which is crucial for such applications.

It is also at the 1-D level where nanowires possess novel electrical and optical properties and exhibit the unique quantum confinement effect [7-14]. The quantum confinement effect is due directly to the size of the wires. The amount of energy (quanta) required to confine excitation levels in nanostructures is increased because the size of the structure is actually smaller than the wavelength of light emitted [15]. This leads to the resultant emitted photons to be of higher energy. By controlling the diameter, growth orientation, length, and crystallinity of the nanowires you can control the wavelength of energy and consequently control the physical, optical, electrical, conductive, chemical and magnetic properties. However, to manufacture 1-D or 0-D structures with economic feasibility and technologic consistency, a new approach is necessary.

There are tremendous ongoing research efforts to grow nanowires and many groups have reported successful synthesis of these nanostructures. H. Cong et al., have produced aluminum nitride (AlN) nanowires [15]. Other groups have exploited materials such as silicon, germanium, gallium, gallium-oxides (Ga_2O_3), gallium-nitrides (GaN) [16]. These wires have high thermal conductivity, high electrical resistivity, good dielectric properties, excellent oxidation resistance, high-temperature strength and can be made optically transparent. The aforementioned properties of these nanowires materials make them ideal for semiconductor applications.

To successfully employ these nanostructures and exploit their unique properties consistent manufacturability must be achieved. Synthesizing nanowires is readily explored and is relatively easily achieved however, obtaining structure and organization on the nanoscale is another task. Each new nanosystem requires considerable research effort and time for optimization (obtaining structure and organization) therefore making the process of growing nanowires unpractical on a manufacturing level. To achieve feasible manufacturability you must have product consistency and high reproducibility, as of yet most nano-systems are not at this level. Nonetheless, anodized aluminum nanopores may possibly help to alleviate some of these problems by providing a simply reproducible substrate which can be employed for different nanostructures; nanowires, nanotubes, etc. The use of these substrates can alleviate the problem of order and structure with good reproducibility.

1.3 Anodization of Aluminum

Anodization is used to passivate aluminum surfaces to produce randomly distributed pores [17]. Matsuda et al. have reported using a two step anodization method to produce regularly distributed nanopores via a self-organization process [18]. Anodization is accomplished by applying an electric current to the aluminum film in the presence of an acidic electrolyte solution as depicted in Figure 2. This leads to a porous surface which can be further exposed via chemical etching. This produces an aluminum substrate which acts as a self-assembled mask for the subsequent anodiztion process and leads to a "honeycomb-like" pattern of nanopores, as shown in Figure 3. The self-assembling of the honeycomb pattern naturally occurs without any intentional means or assistance to the system.

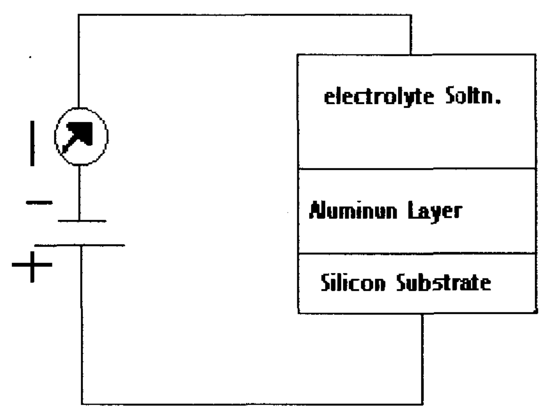


Figure 2. Schematic of setup for anodization of aluminum. The aluminum is contacted with the anode and acidic electrolyte solution with the cathode.

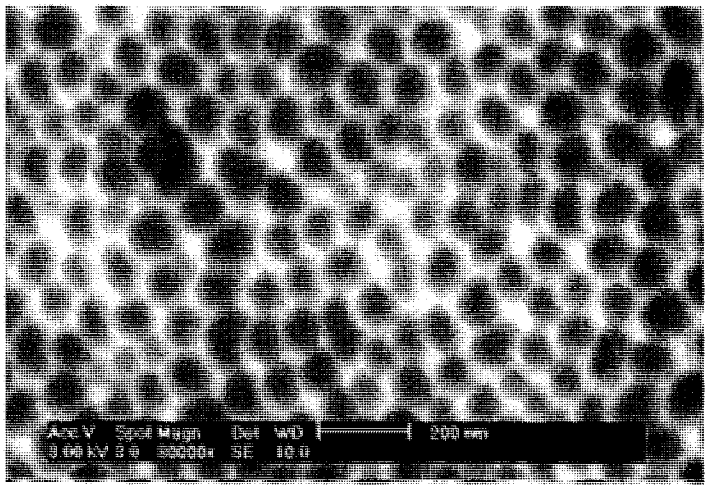


Figure 3. Honeycomb-like patterned nanopores.

2.0 LITERATURE REVIEW

2.1 Anodization of Aluminum film

Anodization of aluminum surfaces for protection or decoration has been employed commercially for at least 80 years [19]. The interest in these self-assembled nanopore structures has been recently increased to the emerging field of nanotechnology. The nanopores provide an ideal structure for the possible growth of nanowires and thus provide order and structure in an otherwise chaotic regular nanowire growth pattern.

F. Li et al. studied pore nucleation and growth. Employing an Al sheet [99.997 % pure, Alfa, with (100) orientation] the group prepared the sheet for anodization using the following steps: 1) The sheet was degreased with a 5 % NaOH solution at 60°C for 30 seconds, rinsed with de-ionized water, neutralized in a 1:1 water/HNO_3 solution for several seconds, and then rinsed again with de-ionized water. 2) The sample was then electropolished in perchloric acid-ethanol solution (165 ml 65 % $HClO_4$, 700 ml ethanol, 100 ml of 2-butoxyethanol and 137 ml of water) at a current density of >500 mA cm^{-2} for 1 minute at, 10°C. 3). The sheet was then washed with warm de-ionized water and then rinsed in cold de-ionized water.

After this initial preparation the sheet was ready for the anodization process. The anodization process is dependent on the acid electrolyte solution, the strength/density of the current and the duration of the current applied. F. Li et al. chose a phosphoric acid solution (H_3PO_4), which should provide a larger pore size, but a slower growth rate for the pore nucleation studies, and carbonic acid ($H_2C_2O_4$) for the pore growth studies [20]. In the pore nucleation studies the Al sheet was anodized at current density of 5 mA cm^{-2}

in a 4 % phosphoric acid solution at room temperature using an aluminum counter electrode. This sheet was then exposed to a solution used for pore widening containing 0.2 M chromic acid (H_2CrO_4) and 0.4 M H_3PO_4 for 15 minutes at 60°C.

The group performed the pore ordering studies as follows: the anodization was done using 40V dc in 3 % $H_2C_2O_4$ at either 0 or 15°C at constant temperature. The anodization process was carried out for 5-10 minutes to eliminate large ridges; the sheet was then submerged in a 0.2 M H_2CrO_4 and 0.4 M H_3PO_4 for 5 minutes at 60°C and re-anodized for 0.5-12 hours to establish long-range ordering. The anodization and acid solution submersion process was repeated several times and finally the final anodization process was repeated for 3 minutes. Subsequent to the final step the aluminum sheet becomes a self-assembled mask for growing highly ordered nanopores as depicted in Figure 4.

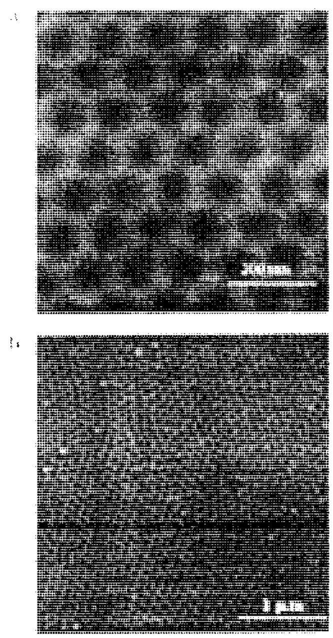


Figure 4. SEM images of anodized aluminum sheet [20].

The characterization of the film surfaces and porosity of the film were determined by using a scanning electron microscope (SEM) and by an atomic force microscope (AFM).

Li et al. concluded that since the measured resistance changes linearly with time there is overall uniform growth of the film. This phenomenon is shown by the graph in Figure 5. It was also conclude that, due to pores merging with adjacent pores, the pore density decreases and pore size increases with increasing time. They attained perfect hexagonal pores (i.e. their best results) with an anodization time of 11.5 hours. This process involved the anodization of the film at 40V dc in 3 % $H_2C_2O_4$ for 10 minutes at 15°C (the process was repeated three times with the oxide being stripped after the first and second anodization), then at 11.5 hour, and finally a 3 minute anodization. However, point defects and misfit locations were found in their samples.

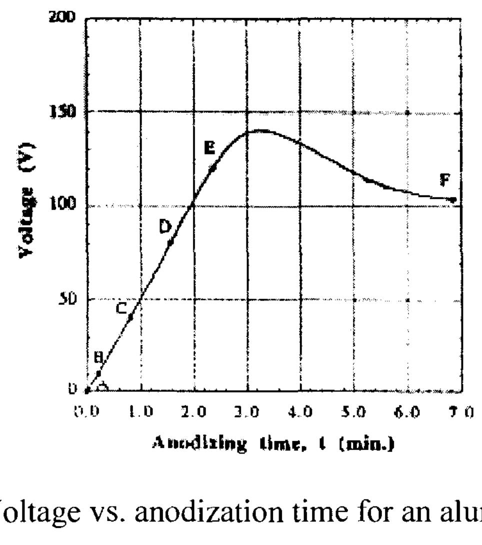


Figure 5. Voltage vs. anodization time for an aluminum sheet [20].

O. Jessensky et al. also performed a similar study using oxalic and sulfuric acid electrolyte solutions [21]. They also used a high purity aluminum film (99.999 %). Their film preparation varied in that they first annealed the aluminum film at 500°C under nitrogen. The film was then electropolished in a 4:4:2 by weight mixture of phosphoric acid, sulfuric acid and water. Subsequently, the film was anodized using a 10 mm exposed area with 0.3 M oxalic acid, 20 wt. % sulfuric acid, the voltage varied from 30 to 60 V, and times varied from 2 to 4 days.

Jessensky et al. then removed the remaining aluminum with a saturated mercury chloride ($HgCl_2$) solution and chemically etched with 5 wt. % phosphoric acid. The best results were obtained when a current of 40 V was employed with an oxalic electrolyte solution as shown by SEM images. This group did not quantify their data; they simply stated which conditions provided the best results. Some results are shown in Figure 6.

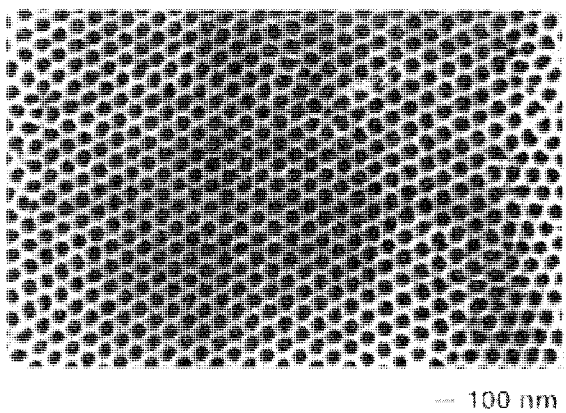


Figure 6. Anodized aluminum film in 0.3M oxalic acid [21].

A. P. Li et al., using a highly pure aluminum film, first degreased the film in acetone and cleaned it in $HF:HNO_3:HCL:H_2O$ = 1:10:20:69 solution [22]. The film was then annealed for 3 hours at 400°C under nitrogen and electropolished in 25:75 mixture of $HClO_4$ and C_2H_5OH. The anodization process was then carried out using oxalic acid, sulfuric acid, and phosphoric acid electrolyte solutions. This group employed the same strategy as O. Jessenky et al. to remove the aluminum and chemically etch the substrate.

The group concluded that the best conditions for anodization and good nanopore growth were with 10 wt. % phosphoric acid solution at 3°C and 160 V, 0.3 M sulfuric acid at 10°C and 25 V, and finally 0.3 M oxalic acid at 1°C and 40 V. These results are shown in Figure 7. These results were qualitative, no data of pore size, density, or other quantitative data was provided in the literature. The duration of the anodization processes with the differing solutions was not provided in this study. The pore widening was carried out for 30 minutes at 30-45°C. This study mainly focused on the inter-pore distance at the varying conditions and acid electrolyte solutions (phosphoric acid, oxalic acid and sulfuric acid). With the phosphoric acid electrolyte solution the pore distances varied linearly with the voltage; 60, 95, and 420 nm with a voltage of 25, 40, and 160 V. With the voltages being varied 19-160 V the overall pore distances varied ~ 50-420 nm. This study concluded that the stress in porous alumina is calculated to be $4.0X10^4$ MPa.

The group later repeated the same study, but with different conditions [23]. The exact same preparation methods were used for the aluminum film and the group repeated the anodization processes with the same electrolyte solutions under the same conditions.

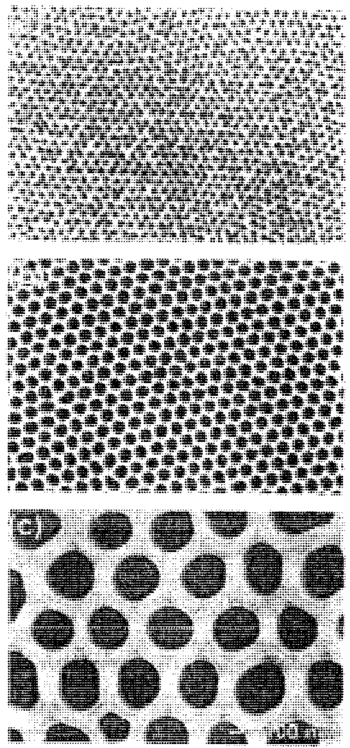


Figure 7. a) Anodized aluminum film in 0.3 M oxalic acid, b) 10 weight % phosphoric acid, c) and 5 weight % phosphoric acid. [22].

However, in this study they used a two-step anodization process. Li et al. removed the first oxide layer by chemical etching with a mixture of 6 wt. % phosphoric acid and 1.8 wt. % chromic acid. The anodization process was then repeated under the same conditions as the first anodization step. This study concluded that pore densities of $6X10^{8}$-$6X10^{10}$ cm^{-2} range were established. They also concluded that removing the oxide layer helped in forming "perfect" ordered pores due to the self-assembled mask provided by the first anodization.

A. Cai et al. did a study on self-assembled nanoporous aluminum oxide on both silicon and silicon oxide substrates [24]. This study differs in that a highly pure aluminum sheet was not used as the substrate. Using an n-type silicon wafer (1-10 **Ω**-cm) a silicon oxide layer of 100-500 nm was deposited via thermal oxidation, then a thin film of titanium of 20 nm was then deposited, and finally via evaporation a Al film of 5-12 μm was formed. The group points out that the titanium layer is crucial to their technique, in that it serves as an adhesion layer that prevents the separation of the Al film from the Si substrate it serves as a barrier layer that prevents the Al-Si alloying during the annealing process, and also serves as a conducting layer. Using the same method, but without the SiO_2 growth a second wafer was prepared. These wafers were then annealed for 400°C for 30 minutes under a nitrogen atmosphere.

Cai et al. then performed electrochemical polishing followed by a wash and dry cycle. The oxide layer formed by exposure to air was then removed just prior to the anodization process. The anodization conditions were as follows: a 4 wt. % solution of oxalic acid at 40 V and 8°C. This study employed the multiple step anodization process. Pore widening was carried out in 5 % phosphoric acid solution at room temperature for 10-50 minutes. The study concluded that ordered pores ranging from 30-70 nm were formed and that the annealing process actually helped with long-range order due to the promotion of grain growth. There was no difference in the pore diameters or long-range order between the film types (aluminum on a silicon and silicon oxide surface).

2.2 Anodization of Aluminum on Silicon

Most of the aforementioned methods employ high purity aluminum films and therefore do not directly apply to my experimental circumstances, albeit, the information presented is pertinent and useful. There are several teams that have developed methods for anodized aluminum on silicon in their attempt to grow carbon nanotubes. J. Li et al. began their anodization process by depositing a highly pure aluminum film (99.999 %) on a substrate [25]. The group achieved 32 nm diameter channels, 6 μm in length, by performing the anodization process at the following conditions; 0.3 M oxalic acid at 15°C under a constant voltage of 40 V.

M. Kim's group applied a thin film (500 nm) on a silicon wafer combined with a template and also used a cobalt-coated substrate (100 Å) on which an aluminum film was deposited [26]. These samples were then electropolished in a solution of perchloric and ethanol to a mirror finish. The anodization process used 0.2 M oxalic acid at 15°C at a constant voltage of 40 V for several minutes. The barrier layer was then removed by dipping the substrates into a solution of phosphoric acid (6 wt. %) and chromic acid (1.8 wt. %) at 60°C. Subsequently, a pore widening step was performed by using a 0.1 M phosphoric acid solution until the desired width was achieved. A second anodization step, under the same conditions, was then carried out to achieve the pores. The average pore diameter was 33 nm and depth being 210 nm for the substrate without the cobalt deposit and 5 nm wide and 220 nm deep for the substrate containing the cobalt sub layer. The group concluded that the major contributing factor on both pore diameter and inter-pore distance was voltage. This is depicted in Figure 8.

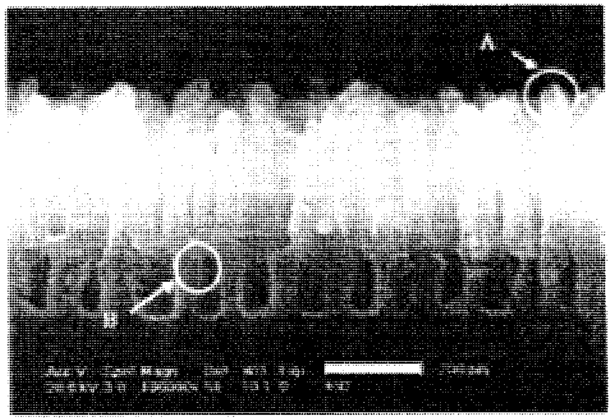


Figure 8. Field enhanced SEM image of carbon nanotubes grown on an anodized aluminum pores. [26].

Another group also used aluminum film deposited on a silicon substrate in attempt to grow carbon nanotubes. W. Hu et al. grew a uniform film layer of 0.5μm and used this substrate in the anodization process [27]. A voltage of 40 V was applied in a solution of 0.2 M oxalic acid solution at 0°C. The sample was the immersed in a solution of phosphoric and chromic acid at 60°C to remove the barrier layer. The resultant film is shown in Figure 9. A second anodization was then carried out under the same conditions. The dimensions of the pores were not provided.

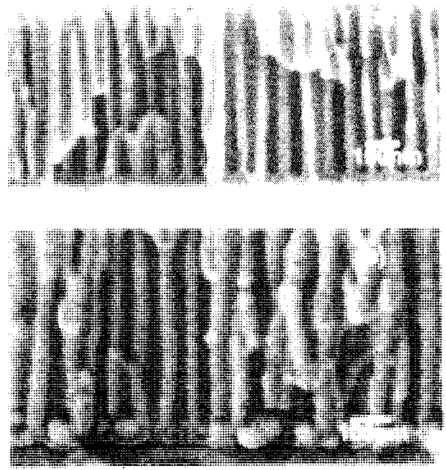


Figure 9. SEM image of an anodized aluminum nanopore array [27].

A summary of the methods and conditions employed by all the aforementioned groups is provided in Table 1.

Table 1. Summary of methods and conditions of reviewed groups.

Group	Substrate	Annealing Process	Cleaning Process	Anodization Solution	Anodization Voltage/Time	Pore Widening	Re-Anodization
O. Jessensky et al.	99.999% Al Sheet	500°C under N_2	4:4:2 Phosphoric Sulfuric Water	0.3M Oxalic Acid	30 – 60 V 2-4 days	5 wt % Phosphoric Acid	Yes
O. Jessensky et al.	99.999% Al Sheet	500°C under N_2	4:4:2 Phosphoric Sulfuric Water	20 wt. % Sulfuric Acid	30 – 60 V 2-4 days	5 wt % Phosphoric Acid	Yes
A.P. Li et al.	99.999% Al Sheet	400°C under N_2	1:10:20:69 HF, HNO3, HCl, H20 Electropolished	10 wt. % Phosphoric Acid	Varied 19-160V	Phosphoric Acid	No
A.P. Li et al.	99.999% Al Sheet	400°C under N_2	1:10:20:69 HF, HNO3, HCl, H20 Electropolished	10 wt. % Phosphoric Acid	Varied 19-160V	Phosphoric Acid	Yes
A. Cai et al.	n-type Silicon w/ Silicon Oxide	400°C under N_2	Electrochemical polishing	4 wt. % Oxalic Acid	40 V	5 wt % Phosphoric Acid	Yes
A. Cai et al.	n-type Silicon w/o Silicon Oxide	400°C under N_2	Electrochemical polishing	10 wt. % Phosphoric Acid	Varied 19-160V	5 wt % Phosphoric Acid	Yes
J. Li et al.	Silicon Wafer	N/A	N/A	0.3 M Oxalic Acid	40 V	N/A	N/A
M. Kim et al.	Silicon Wafer	N/A	Perchloric Acid/Ethanol Solution	0.2 M Oxalic Acid	40 V	0.1 M Phosphoric Acid	Yes
M. Kim et al.	Silicon Wafer w/Cobalt	N/A	Perchloric Acid/Ethanol Solution	0.2 M Oxalic Acid	40 V	0.1 M Phosphoric Acid	Yes
W. Hu et al.	Silicon Wafer	N/A	N/A	0.2 M Oxalic Acid	40 V	Chromic Acid/ Phosphoric Acid	Yes

2.3 Proposed Mechanisms

Hexagonal nanopore formation is not clearly understood. The mechanism for the hexagonal formation of the nanopores is described differently by different studies. Several mechanistic existing theories include the stress induced mechanism, the chemical process, and self-organization method.

A.P. Li et al. conclude that the stress mechanism is responsible for the observed hexagonal pattern of the assembled nanopores [22]. This study shows the volume expansion factor for aluminum without the pores is roughly 1.28 and the volume expansion for the porous aluminum is about 1.4 and corresponds to a linear strain of 0.12. They conclude the Young's modulus is roughly $4.0X10^3$ MPa for the porous alumina and assume that the ordered domain size is related to the stress and relaxation in the alumina layer. Similar stress values give similar ordered patterns.

F. Li et al. describe the formation via a chemical model. The reactions are explained with the following mechanism [20]:

Al^{3+} ions form at the metal/oxide interface:

$$Al(s) \rightarrow Al^{3+}(oxide) + 3e^- \qquad \text{Equation 1}$$

The oxide/electrolyte interface the water-splitting reaction, this is considered the rate determining step:

$$3/2\ H_20(l) \rightarrow 3H^+\ (aq) + 3/2\ O^{2-}(oxide) \qquad \text{Equation 2}$$

The O^{2-} (oxide) ions migrate due to the electric field and form Al_2O_3 at the metal/oxide interface. The protons can locally dissolve more oxide:

$$1/2Al_2O_3(s) + 3H^+(aq) \rightarrow Al^{3+}(aq) + 3/2H_2O(l) \qquad \text{Equation 3}$$

The hydronium ions can also migrate toward the cathode, where they leave the system in the form of hydrogen and complete the circuit:

$$3H^+(aq) + 3e^- \rightarrow 3/2H_2(g) \qquad \text{Equation 4}$$

O. Jessensky et al. describe a self-organization model for the nanopore formation. They explain the chemistry essentially as described by F. Li et al., but combine it with the stress mechanism as described by A. P. Li et al. The study says, "A possible origin of forces between neighboring pores is therefore the mechanical stress which is associated with the expansion during oxide formation at the metal/oxide interface." Another possible explanation of this phenomenon may be that the honeycomb like self-assembled pattern is most closely packed and fills the provided space most efficiently. Systems tend to migrate toward what is described as the lowest energy state and this particular orientation may result in the lowest energy structure and hence, such an arrangement is observed.

2.4 Assessment of Previous Studies

The available literature provides tremendous insight into the overall anodization process for aluminum thin films. Each group successfully accomplished complete anodization regardless of the substrate type, voltage settings, difference in acid electrolyte or pore widening solutions, solution concentrations, or cleaning and preparation processes. Although the groups varied in their preference of the aforementioned experimental parameters, no group varied any of the parameters themselves. From the literature it can be inferred that effects of solution concentrations, voltage, and temperature are the major factors in controlling the pore size, dimensions, and overall morphology of the anodized aluminum films.

3.0 RESEARCH STATEMENT AND OBJECTIVES

3.1 Objectives

The research objectives of this thesis are to study the effects of varying the applied voltage and acid concentrations of electrolyte and pore widening solutions on pore size, density, and tortuosity.

A subsequent brief study was done to investigate the temperature effects on the pore properties of the thin film. Anodization of a 0.5 μm deposited aluminum film, on a silicon wafer, can be achieved via electrochemistry. By varying the acidic electrolyte solutions as well as the voltage of the system, the resultant nanopore diameter, density, and length can be controlled.

4.0 MATERIALS AND EXPERIMENTAL PROCEDURE

4.1 Materials

Materials used are given in Appendix A.

4.2 Analytical Method

An aluminum film of fixed thickness was deposited on a highly doped Si <111> substrate (0.001 – 0.005 Ωcm) by ion beam sputtering. The sputter employed for this process is communal and consequently metal targets and flow conditions are constantly being changed. In an attempt to alleviate variances from the sputterer the aluminum and titanium targets were run for 5 minutes before the actual deposition process. The flow rates (deposition rates) were closely monitored to provide consistency. This film was anodized via an electrochemical process utilizing an acidic electrolyte solution, chemical etching solution, and controlled voltage and current. The resultant pore arrays were characterized using a scanning electron microscope. It was shown that the size of the ordered domains is a function of the solution concentrations and the anodizing voltage.

4.2.1 Experimental Procedure

Nanopore development on an aluminum surface via anodization is a widely explored subject; however, the majority of the literature available cites pure aluminum sheets as the substrate. The use of a silicon substrate with a deposited aluminum film is not as thoroughly explored. The literature available did however provide some crucial insight to the overall process. It is emphasized that the initial anodization step, in a two-step anodization process, is critical. The first step of the overall process generates the primary pores, which then act as a self-assembled mask for the subsequent anodization. An initial study was conducted to explore the most advantageous conditions for the first anodization step for our system. Based upon a successful completion of this study an anodization time was selected. To explore the effects of electrolyte concentrations and voltage a design-of-experiment matrix was utilized. Table 2 shows the initial conditions explored for the first anodization step.

Table 2. Preliminary anodization study.

Experiment #	# Of Samples	Temperature	Film Thickness	Voltage	Anodization Time (min.)
1	1	22^{o} C	3 μm	40 V	5
2	1	22^{o} C	3 μm	40 V	15
3	1	22^{o} C	3 μm	40 V	30
4	1	22^{o} C	3 μm	40 V	60
5	1	22^{o} C	3 μm	40 V	180

4.2.2 Two Levels by Three Parameters Interaction Study

The interaction of acid electrolyte solution concentration, pore-widening acid concentration, and voltage was explored utilizing a design-of-experiment matrix. The film thicknesses, deposited metal type, temperature and current were held constant in this study. The design-of-experiment is outlined in Table 3.

Table 3. 2^3 Design of experiment matrix.

Parameters	Definition of Effects		
	-	+	Units
Conc. oxalic acid (COA)	0.1	0.7	Moles/Liter
Conc. H_3PO_4 (CPA)	0.2	0.6	Moles/Liter
Voltage (V)	30	50	Volts

Run	Sample	COA	CPA	V	COA-CPA	COA-V	CPA-V
1	1	-	-	+	+	-	-
2	1	-	-	-	+	+	+
3	1	-	+	+	-	-	+
4	1	-	+	-	-	+	-
5	1	+	-	+	-	+	-
6	1	+	-	-	-	-	+
7	1	+	+	+	+	+	+
8	1	+	+	-	+	-	-

4.2.3 Temperature and Grain Size Study

The center point conditions were applied in ensuing experiments to explore the temperature effects on the substrate and the grain size of the deposited films. The temperature was varied for three conditions, 0°C, 22°C, and 48°C. A summary of the proposed study is shown in Table 4. The temperature effect was not generally explored in the literature; this subsequent study will provide an indication of the effects of temperature on the system. The temperature was controlled using a circulating pump, which forces the water from a fixed temperature water bath through the cell containing the electrolyte solution. This is shown in Figure 10. The inside chamber of the cell is of uniform diameter.

The grain size of the sputtered aluminum film was measured via atomic force microscopy and compared with tortuosity and nanopore diameter values.

Table 4. Temperature study.

Run	Sample	Temperature
1	1	0°C
2	1	22°C
3	1	48°C

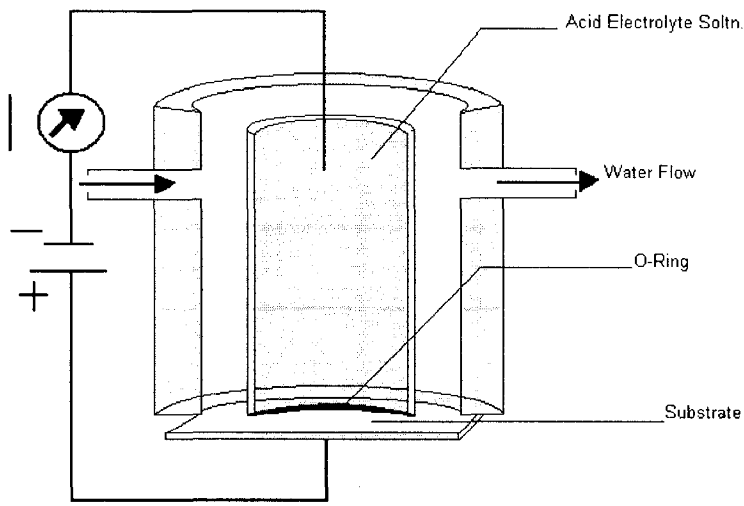


Figure 10. Basic cell schematic. Inside chamber measures 1.1 cm (diameter) x 4.7 cm 4.7 cm (height) and is uniform throughout the cell. The outer cylindrical annular region has an inside diameter of 1.1 cm, an outside diameter of 1.6 cm, is 4.7 cm in height, and is uniform throughout.

4.2.4 Control Runs

Two control samples (pure silicon and pure titanium) at the center point conditions were anodized to show that the anodization process does not penetrate these layers. The titanium film was 250 nm thick. To serve as controls for the DOE, three center runs were interspersed throughout the experimental schedule. Center point condition runs were interspersed throughout the matrix to show repeatability and reproducibility of the experiments. The experiments were conducted using 0.3 M oxalic acid, 0.4 M phosphoric acid, and at a set voltage of 40 V.

4.2.5 Voltage and Current Control

The voltage was controlled by a Hewlett Packard DC Power Supply, model # E3612A. The current is automatically varied by the power supply. The power supply has a range from 0-115 V.

4.2.6 Film Deposition

To accomplish cleaning of the substrates a standard wafer cleaning process utilized by the semiconductor industry was employed:

I. A silicon substrate was first immersed in isopropyl alcohol and placed in a sonication bath for 5 minutes. It was then removed and thoroughly rinsed with distilled water.

II. The alcohol cleaned substrate was then positioned in a HF bath containing a solution of 20% concentration for another 5 minutes. Once the substrate was removed from the HF solution it was again washed with distilled water.

III. The acid cleaned substrate was then placed in the IBS/TM200S Ion Beam Sputter to begin the sputtering process. The sputtering process involves two steps. Initially a 25 nm layer of titanium is deposited and then subsequently the deposition of a 0.5 μm layer of aluminum follows. The titanium layer provides film adhesion between the aluminum and silicon surfaces and also serves as a conducting layer. This technique was taken from the study by A. Cai et al [26].

IV. The substrate was then placed in the cell and fastened into position. This configuration is illustrated in Figure 10. The cell is filled with the acid electrolyte solution and the circuit completed by introducing the platinum cathode.

4.2.7 Data Collection and Analysis

The data was analyzed by observing the morphology of the nanopores. This focuses on the pore density (pores/cm^2), the mean pore diameters, and pore tortuosity. This was accomplished using a scanning electron microscope (SEM). The diameter of the pores were measured and mean values were determined. The tortuosity was measured as the total length of the tortuous path divided by the measured film thickness. This value was normalized to the least tortuous pores. The formulas used in the calculations are summarized in Table 5.

Table 5. Formulas for Data Analysis

Mean	$m = \frac{1}{n}\sum_{k=1}^{n} x_k$	Equation 5
Pore Density	# of Pores/cm^2	Equation 6
Pore Tortuosity	$\tau = \frac{\sum_{i=1}^{n} P_i D_i}{\# Pores \times FilmThickness}$	Equation 7

Where P_i and D_i is the number of pores and total distance, respectively.

To obtain side and top profile SEM images of the anodized area of the substrate is thoroughly cleaved at the center to reveal the edge. The images are then captured by a Hitachi S-4000 SEM at 20 keV and 20 Amps. The images were taken at several areas of the chip as portrayed in Figure 11. Metric 7.1 DEMO Plus software was employed in obtaining the dimensions (diameter, length, and density) from the SEM images.

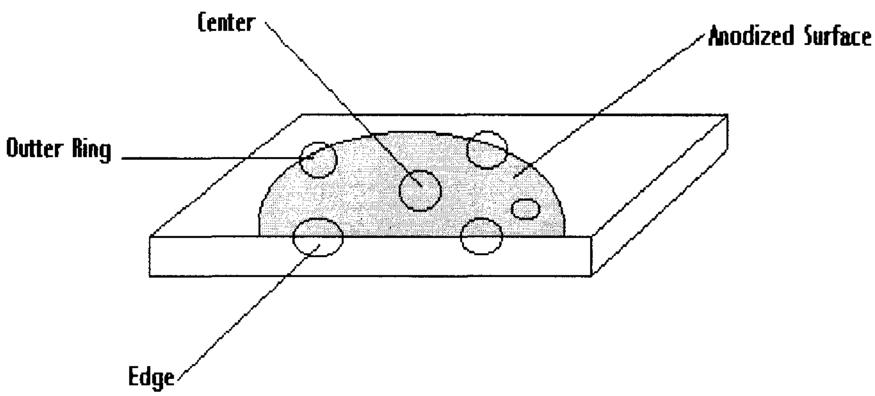


Figure 11. SEM imaging locations on anodized substrate

4.2.8 Data Analysis with Metric Plus 7.1 Demo

All of the captured SEM images were imported into Metric Plus software for analysis. This software was employed for acquiring the raw data for pore diameter, length, and density. An example of each type of image imported into Metric Plus is shown in Figures 12, 13, and 14.

Two types measurements were explore for each substrate; diameter and length. Length was then used to calculate the tortuosity. A minimum of 200 and up to 250 data points were obtained for each substrate to analyze nanopore diameters. A minimum of 60 and up to 125 data points were taken for each substrate to investigate the nanopore lengths. Only completely anodized pores were looked at in this study. Complete anodization is defined as a pore which when observed from a top down view is completely dark and when surveyed from a side profile has completely anodized from the top of the aluminum layer to the titanium sub layer without interruption.

Pore diameter was attained by designating three points on the circumference of the pore. The software then constructed a circle and assigned a value to the diameter of that generated circle. However, these values were only given in micrometers, as this was a demonstration version and the scale characteristic was fixed. Each value was then converted to the correct measurement using a scaling factor. This scaling factor was obtained by measuring the given scale on the legend of each SEM image and correlating it to exact measurement in micrometers. As the magnification of each image changed, so did the given scale of each SEM image and hence the scaling factor. An example conversion is represented by equation 8.

In Equation 8 the value of 127 μm is generated by the software upon designating three points on the nanopore circumference, however this is not the true measurement. The scaling factor employed is as follows: 500 nm on the SEM image is equal to 1425 μm as measured by Metric Plus. After adjusting for the discrepancy in scale the observed value of 127 μm is in fact 44.46 nm. Each image has a unique scaling factor (listed with images in Appendices B- M) which was utilized in determining the true diameter measurements.

$$127um \times \frac{500nm}{1425um} = 44.46nm \qquad \text{Equation 8}$$

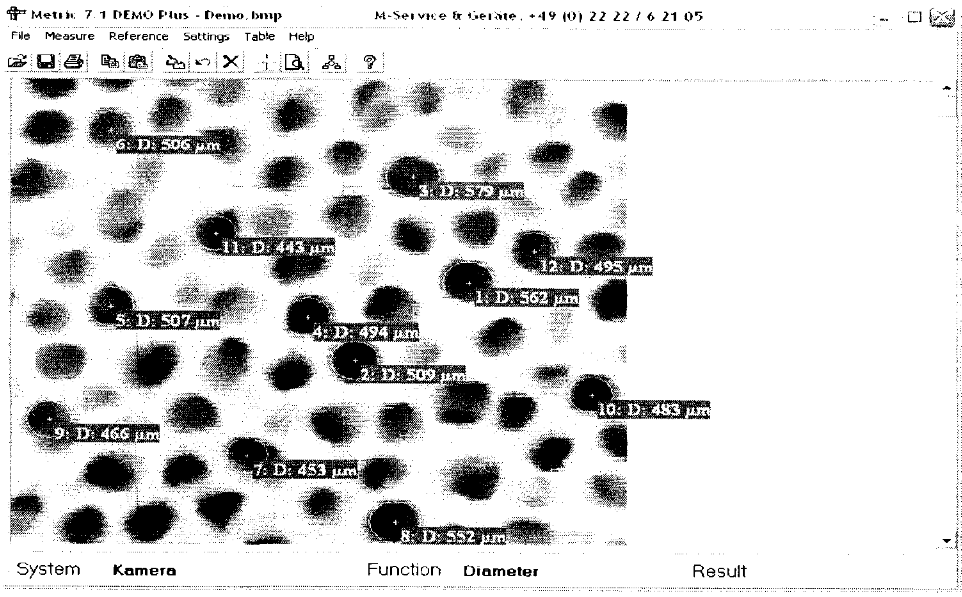


Figure 12. SEM Image of anodized aluminum film for diameter measurements using Metric 7.1 DEMO Plus software.

The nanopore density was determined by counting the number of complete pores on each image. All of the SEM images measured 6400 µm X 6400 µm as established by the Metric Plus Software and once again a scaling factor was exploited in determining the true density. Equation 9 shows a sample conversion.

$$\left[695 pores \div \left(6400um \times \frac{500nm}{1425um}\right)^2\right] = \left(1.38e^{-4}\, pores/_{nm^2}\right) \times \left(\frac{\left(1e^7 nm\right)^2}{1cm^2}\right) = 1.38e^{10}\, pores/_{cm^2} \qquad \text{Equation 9}$$

For this particular SEM image 695 total pores were counted. Using the scaling factor of 500 nm on the SEM legend is equal to 1425 µm as measured by the software the surface area is scaled to its true value. 695 pores are divided into this area to reveal $1.38e^{-4}$ pores/nm^2 and this value is then converted to pores/cm^2. It is reiterated; each image has a unique scaling factor which was utilized in determining the true densities.

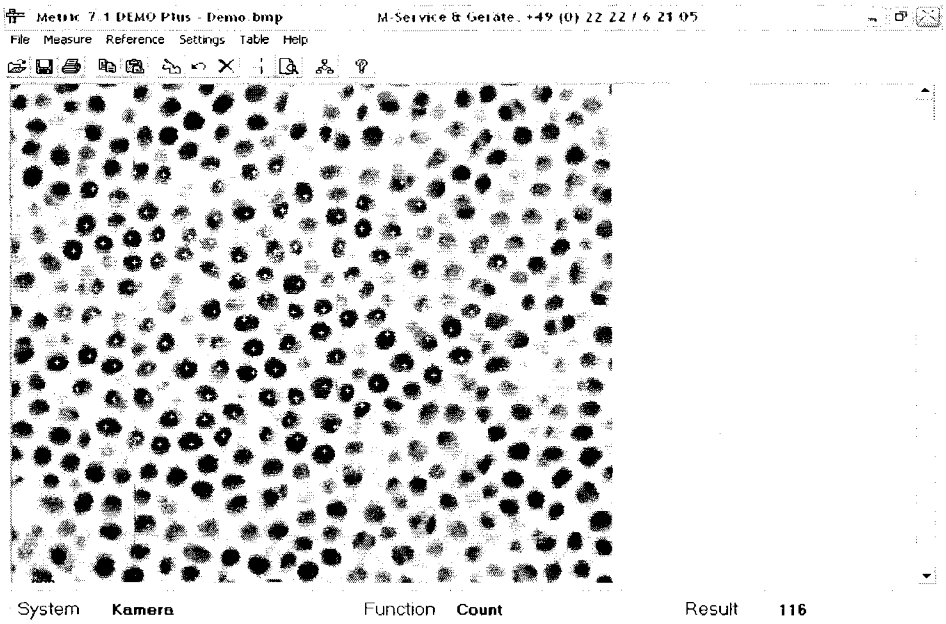


Figure 13. SEM Image of anodized aluminum film for nanopore density count using Metric 7.1 DEMO Plus software.

Tortuosity was calculated using the mean length of the nanopores and consequently the length for each nanopore was ascertained via Metric Plus Software. The length was found by following the path of the nanopore and designating any deviation from a perpendicular path. The software then recognized these designations and calculated a total length based a continuous chain measurement. Each observed value once again had to be converted to its true value. Equation 10 demonstrates this conversion.

In Equation 10 the value of 1276 μm is the observed software value. The scaling factor employed is as follows: 500 nm on the SEM image is equal to 938 μm as measured by Metric Plus. After adjusting for the discrepancy in scale the observed value of 1276 μm is fact 680.17 nm. Once again, each image has a unique scaling factor which was utilized in determining the true length measurements for each observation. The standard method for reporting these aforementioned values is in size per pixel, however I have deviated from this unit and reported actual diameters, densities, and lengths.

$$1276um \times \frac{500nm}{938um} = 680.17nm \qquad \text{Equation 10}$$

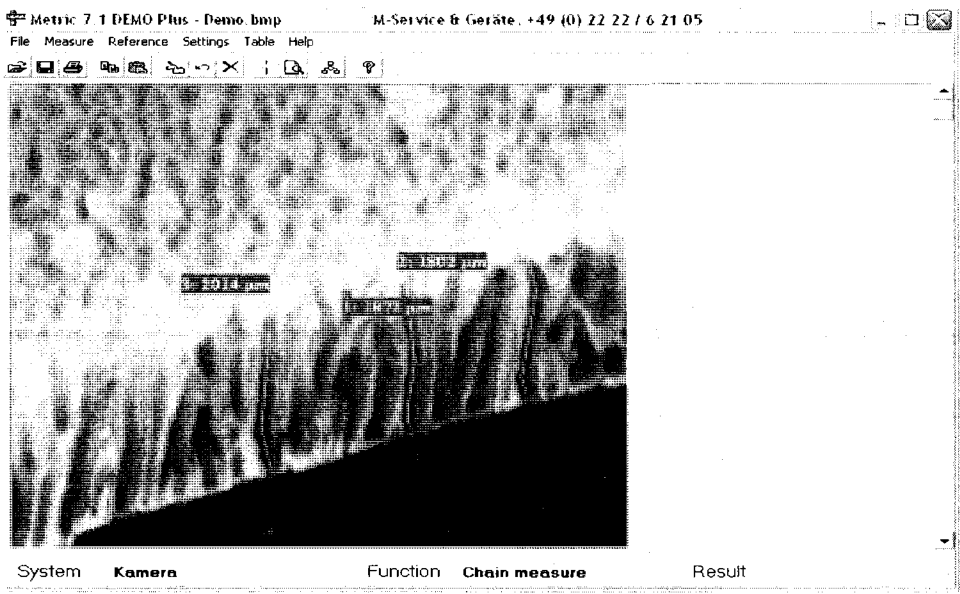


Figure 14. SEM Image of anodized aluminum film for pore length measurements using Metric 7.1 DEMO Plus software.

4.2.9 Error of Means

Once the raw data is acquired with the software the mean of each characteristic are determined. The experiments that have multiple runs are used in determining the error values for all substrates. The center point run is conducted three times and will be used in providing error analysis. The error values will be determined via equation 11 and be applied as a percentage to each characteristic (diameter, density, and tortuosity).

$$\sigma_{\bar{X}} = \frac{\sigma_X}{\sqrt{N}} = \sqrt{\frac{\Sigma\left(X_1 - \bar{X}\right)^2}{N(N-1)}} \qquad \text{Equation 11}$$

Where N is the number of samples, X_1 is each value, and X is the average of those values.

5.0 RESULTS AND DISCUSSION

The initial anodization of the aluminum film forms nanopores, which then act as a self-assembled mask for the subsequent anodization process. The density and size of these pores dictates the quality of the finished product. Therefore, it is imperative that an appropriate time interval be determined that leads to the desired results. Table 2 provides the initial conditions and time intervals explored. See Figure 15 for the results of this preliminary study.

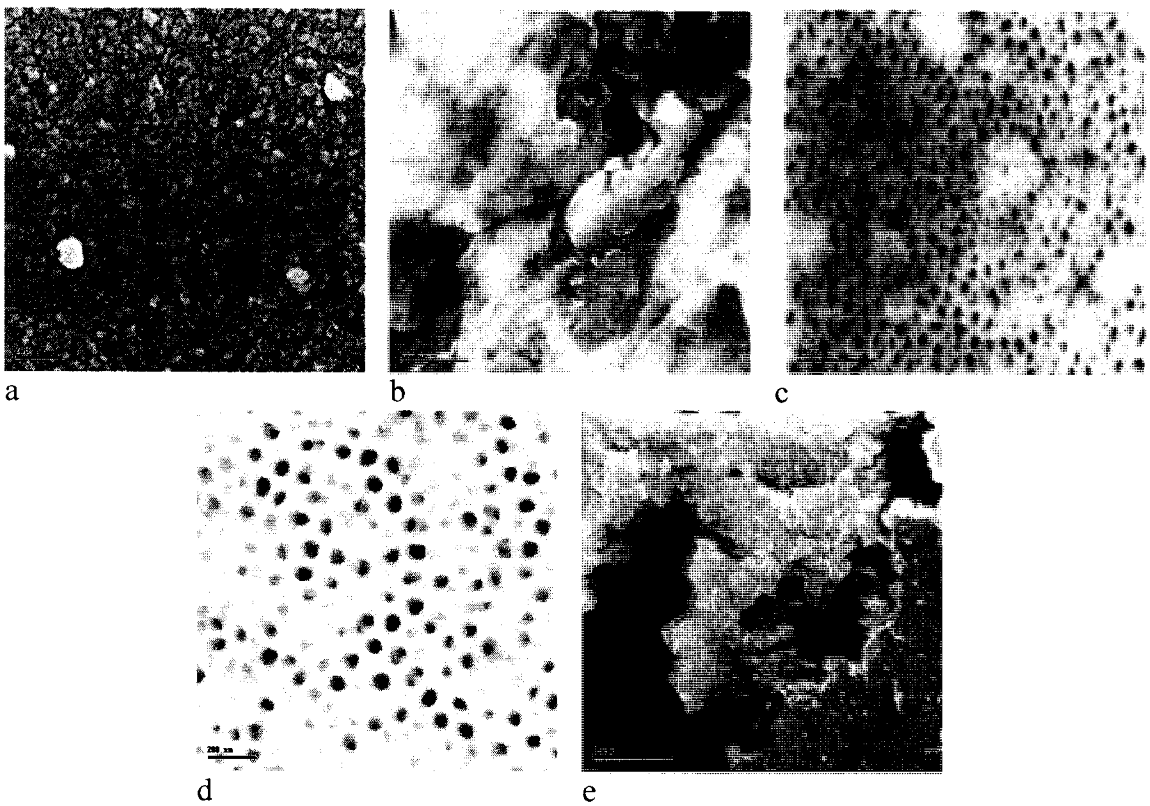


Figure 15. SEM images of the aluminum film at different anodization times: a) aluminum film after 5 minutes; image at 45 K, b) aluminum film after 15 minutes; image at 30 K, c) aluminum film after 30 minutes; image at 30 K, d) aluminum film after 60 minutes; image at 45 K, and e) aluminum film after 180 minutes; image at 30 X.

From the images it is apparent that an initial anodization time of 60 minutes is best for our pre-determined nanopore dimensions. It provides a good starting point to accomplish the final desired pore width (10-100 nm) as well as depth (100-500 nm). The 5 minute and 15 minute anodization times fail to yield nanopores and a 180 minute anodization time destroys the aluminum film. The 30 minute anodization time produces low quality pores (too small, shallow, and incomplete) and therefore is not satisfactory. The amount of time allotted for the preliminary anodization, chemical etch, and final anodization process influences the overall morphology of the pores. The scope of this study does not explore the effects of time on each phase of the process; therefore these intervals were fixed at 60 minutes per each step (initial anodization, etching, and final anodization). This time interval allows for sufficient anodization and etching. There was no concurrence on the anodization time cited in the literature, each group varied greatly in the time allotted for each step. As an example, the primary anodization step varied from 15 minutes to 48 hours, therefore this study was vital in establishing a time interval.

5.1 Main Effects

The desired pore morphology is a diameter value of 50-100 nm, high density, and a low overall tortuosity. It is understood that these values are dependent on acid electrolyte concentrations as well as the intensity of the applied voltage and vary with changing conditions. In order to observe the effects of these variables and determine the most favorable conditions, design of experiments (DOE) is employed. This analytical method allows one to explore the effects of acid electrolyte solutions and voltage on the pore diameter, density, and length by varying the conditions simultaneously. This section will explore the main effects and the results of the varying conditions on the nanopore characteristics. Table 3 can be used as a reference for the initial conditions, concentration, and voltage settings. The center point values are: 0.3 M oxalic acid, 0.4 M phosphoric acid, and a set voltage of 40 volts. The mean pore diameter, tortuosity, and densities were calculated as explained in Table 5.

The DOE consists of a schedule of 8 randomized runs with three interspersed center point runs. After the anodization process the resultant substrates are cleaved and a scanning electron microscope (SEM) is utilized for characterization. For diameter and density measurements a top view is exploited and to capture nanopore lengths a side profile is utilized; four images are captured per substrate, per attribute.

5.1.1 Main Effects on Nanopore Diameter

The effects of acid concentrations and voltage intensity were explored via DOE on nanopore diameter. The resultant DOE mean scores and factor effects were calculated and shown in Table 6. From the resultant calculations it can be said that voltage has the greatest effect on the pore diameter, it increases the pore diameter by 15.42 nm. The concentration of phosphoric acid also has a significant effect. The phosphoric electrolyte solution has a score of 10.15 nm and also influences the pore diameter significantly, albeit not to the same degree as voltage. Of the three variables the results clearly indicate that voltage has the largest effect. These effects are without any significant interactions as indicated by the interaction effect scores.

Table 6. Factor effects of the DOE for pore diameters.

Run	Sample	COA	CPA	V	COA-CPA	COA-V	CPA-V	Mean Diameter (nm)
1	1	-	-	+	+	-	-	49.73 ± 6.40 %
2	1	-	-	-	+	+	+	49.43 ± 6.40 %
3	1	-	+	+	-	-	+	75.28 ± 6.40 %
4	1	-	+	-	-	+	-	53.14 ± 6.40 %
5	1	+	-	+	-	+	-	63.71 ± 6.40 %
6	1	+	-	-	-	-	+	40.05 ± 6.40 %
7	1	+	+	+	+	+	+	65.34 ±6.40 %
8	1	+	+	-	+	-	-	49.75 ±6.40 %
Divisor		4	4	4	4	4	4	
Effects:		- 2.19	10.15	15.42	-4.49	4.20	3.44	
Mean	55.81							

Parameters	Definition of Effects		
	-	+	Units
Conc. oxalic acid (COA)	0.1	0.7	Moles/Liter
Conc. H_3PO_4 (CPA)	0.2	0.6	Moles/Liter
Voltage (V)	30	50	Volts

From the DOE table the response factors for each variable were also calculated. Figures 16, 17, and 18 show the plots of these response factors. The response factor plots indicate that the diameter values can be controlled by adjusting the DOE variables to the appropriate settings. To achieve an overall larger mean diameter the voltage setting should be 50 volts, the concentration of oxalic acid should be 0.2 M, and the concentration of phosphoric acid must be set at 0.6 M. The converse of each variable setting is true to realize a generally smaller mean diameter. A target range of 10 -100 nm range was established for the nanopore diameter.

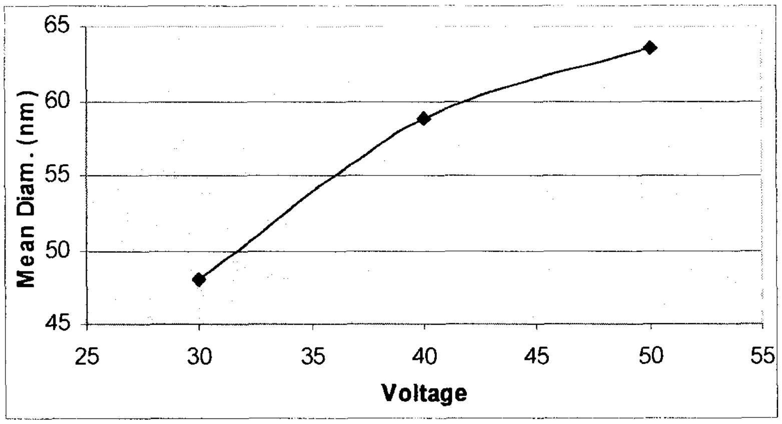


Figure 16. Response factor for voltage versus mean pore diameter.

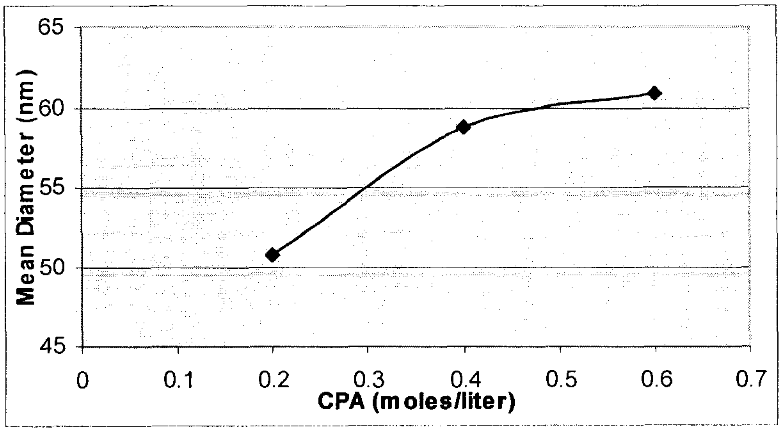


Figure 17. Response factor for concentration of phosphoric acid versus mean pore diameter.

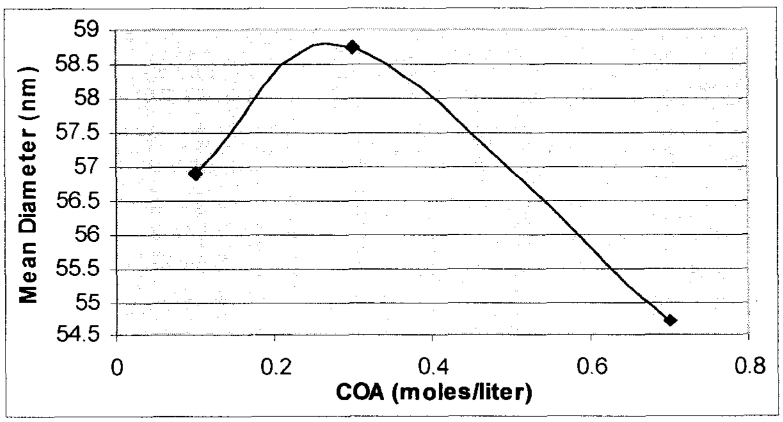


Figure 18. Response factor for concentration of oxalic acid versus mean pore diameter.

The effect of voltage seems to be the greatest controlling variable on the overall magnitude of the nanopore diameters. The lower voltage (30 volts) produced a mean diameter value of 48.09 nm, whereas the higher setting of 50 volts produced a mean diameter of 63.52 nm. The voltage may control the rate of the reaction, since this process is not mass flow limited, the rate of the reaction may increase with the higher voltage, much as most reaction rates increase with an increase in temperature. This increased rate of reaction may cause more rapid pore nucleation of adjacent pores and thus produces larger diameter pores. When the voltage is set lower this mechanism is slowed resulting in smaller overall diameters.

The phosphoric acid solution gave a mean diameter of 50.73 nm at a 0.2 M concentration and 60.88 nm at 0.6 M. The effective voltage is applied in two steps of the process, where the phosphoric acid is only made use of in the pore widening step, but still had an appreciable effect. On page 19 of section 2.3 a proposed mechanism is described by F. Li et al. in which aluminum oxide is formed at the metal/oxide surface and is dissolved away by hydrogen ions. If the acid concentration is sufficiently low, the field-assisted hydrogen ion attack on the oxide layer may slow or stop and form a barrier type film. If this is the case, then the use of a higher concentration phosphoric electrolyte solution as a pore widening agent removes more of this barrier type film layer. This allows for a more rapid reaction rate and consequently superior pore nucleation, resulting in a larger mean diameter, whereas, employment of a lower concentration solution does not as readily remove the layer and thus results in a slowed reaction rate and less pore nucleation and an overall smaller average diameter.

The concentration of oxalic acid seems to have a maximum effect at around 0.3M, producing a mean diameter of 58.74 nm. At the explored higher and lower concentrations the effective mean diameter is reduced. At the lower concentration there may not be enough hydrogen ions present to achieve a larger diameter, and at the other end of the spectrum (0.7 M), the hydrogen concentration may be too great and the field assisted attack has too many nucleation sites and pore nucleation is slowed.

5.1.2 Main Effects on Nanopore Density

Nanopore density is measured in terms of pores per area of squared centimeter. This value, when combined with the nanopore diameter, will give an idea as to how many nanopores are present when a particular pore width is achieved. A low or high density may be preferred depending on the desired application. The effects of acid concentrations and strength of voltage were also explored for this attribute.

Once again, the DOE matrix was utilized to show the mean scores and factor effects. This resultant matrix is shown in Table 7.

Table 7. Factor effects of the DOE for pore density.

Run	Sample	COA	CPA	V	COA-CPA	COA-V	CPA-V	Ave. Density
1	1	-	-	+	+	-	-	9.31e+09 ± 20.52 %
2	1	-	-	-	+	+	+	1.61e+10 ± 20.52 %
3	1	-	+	+	-	-	+	8.65e+09 ± 20.52 %
4	1	-	+	-	-	+	-	1.96e+10 ± 20.52 %
5	1	+	-	+	-	+	-	1.06e+10 ± 20.52 %
6	1	+	-	-	-	-	+	2.20e+10 ± 20.52 %
7	1	+	+	+	+	+	+	9.60e+09 ± 20.52 %
8	1	+	+	-	+	-	-	2.07e+10 ± 20.52 %
Divisor		4	4	4	4	4	4	
Effects:		2.30e+09	1.23e+08	-1.01e+10	-1.29e+09	-1.16e+09	-9.81e+08	
Mean	1.46e+10							

Parameters	Definition of Effects		
	-	+	Units
Conc. oxalic acid (COA)	0.1	0.7	Moles/Liter
Conc. H_3PO_4 (CPA)	0.2	0.6	Moles/Liter
Voltage (V)	30	50	Volts

The calculated design of experiment effects show that the largest negative effect is due to voltage. Voltage decreases the pore count as much as 1.01 X 10^{10} pores/cm^2. No such statement can be made of the acid electrolyte solutions due to a strong interaction effect between the phosphoric and oxalic acid concentrations. A high voltage combined with a low concentration of oxalic acid (0.1 M) and a high concentration of phosphoric (0.4 M) acid results in the least dense substrate. The densest substrate, in terms of pores per square centimeter, is achieved with a low voltage, high oxalic (0.7 M) acid concentration, and a low phosphoric acid concentration (0.2 M).

The response factors for each variable versus nanopore density were also calculated. Figures 19, 20, and 21 show the plots the aforementioned response factors. It can be inferred from these figures that a higher nanopore density is achieved by applying a lower effective voltage and a higher concentration of phosphoric and oxalic acid electrolyte solutions.

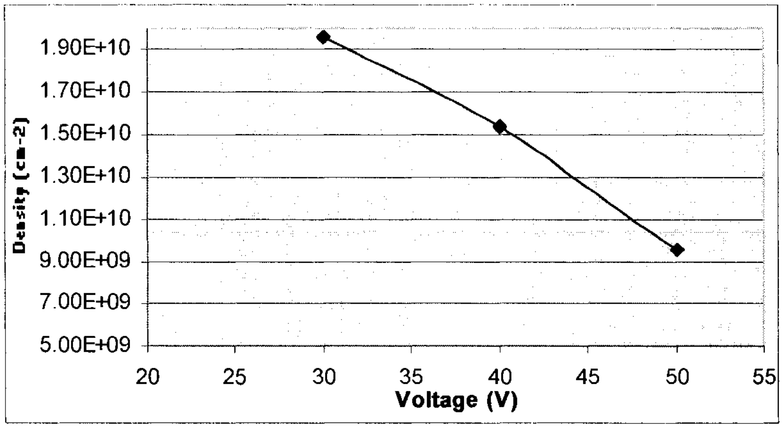


Figure 19. Response factor for voltage versus mean pore density.

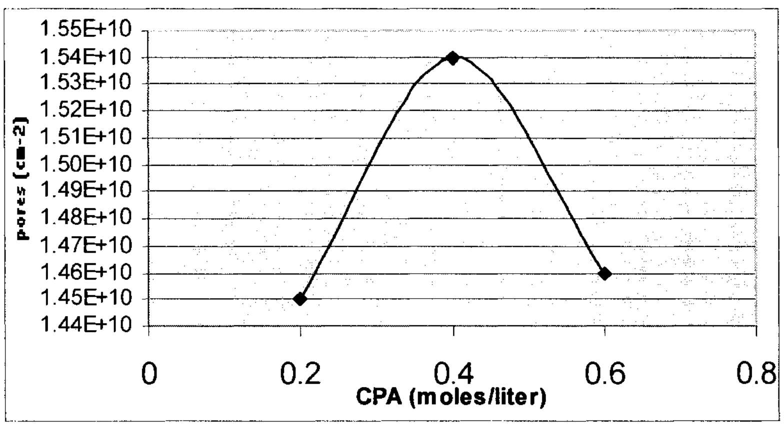


Figure 20. Response factor for concentration of phosphoric acid and density.

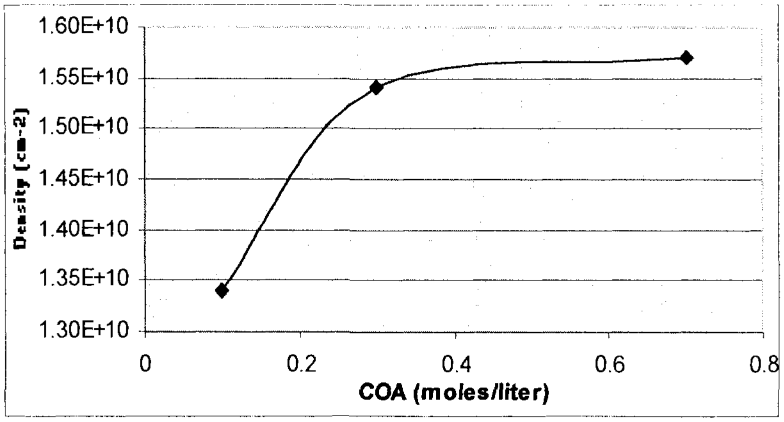


Figure 21. Response factor for oxalic acid concentration and pore density.

In terms of the nanopore density it is apparent that a lower voltage and higher acid concentrations result in a more desirable morphology, i.e. a more dense substrate. This is in accord with previous observations. The higher the voltage the greater the rate of adjacent pore nucleation, thus, as formerly described, the greater the pore diameter. However, if the voltage is lower the general nucleation process is slowed and therefore there are a greater number of pores, albeit resulting in a sacrifice of smaller nanopore diameter width. A change in oxalic and phosphoric acid concentrations also assists in increasing or decreasing the nanopore density. The higher oxalic acid concentration provides a greater number of hydrogen ions present during the anodization process and hence, elevates the ions accessible per attack site on the oxide layer; the greater the concentration, the faster the process occurs. The increase in concentration may assist in attacking at more locations and consequently result in a greater density. Also, the chemical dissolution of the oxide layer at the electrolyte/oxide interface is an exothermic process and may cause a localized temperature increase. This phenomenon may result in an increased rate of reaction at the surface of the substrate; consequently a higher electrolyte concentration combined with an increased reaction rate may sustain more attack sites and help explain the increase in density.

The phosphoric acid is only employed in the pore widening step and as explained earlier the higher concentration better helps to remove any barrier type film that may exist and thus foster a more complete second anodization. The phosphoric concentration has a maximum at about 0.4 M, which results in a density of 1.54 e^{10} pores/cm^2. This phenomenon is difficult to explain. The higher the concentration the more effectively the barrier type film should be removed. One possible explanation may be that there simply exists a middle concentration that effectively removes the barrier type film more readily than a lower or higher concentration, i.e. the stoichiometric ratio between the acid and film is better suited at the middle concentration. This phenomenon may need further investigation.

The effective voltage is probably the greatest contributing factor in increasing or decreasing the pore density because of its overall effect on the nanopore diameter. As the diameter of the nanopores increase the overall density decreases and since voltage was the largest contributing factor to the diameter size, accordingly it impacts the substrate densities.

5.1.3 Main Effects on Nanopore Tortuosity

Tortuosity is defined as the average length of the flow path of a fluid particle from one side the porous medium to the other; the more tortuous the path the longer the fluid has to travel. The desired tortuosity, according to equation three of Table 5, is one. For a tortuosity value of one or close to one means the pores are almost perfectly perpendicular and completely anodized from the surface of the aluminum film to the titanium sub layer. This array orientation and tortuosity value is desired because it implies high pore ordering. The voltage and acid concentrations also directly impact nanopore length and, in turn, the tortuosity assessment. Incomplete anodization in the primary step of the overall process or incomplete etching in the secondary phase can lead to multiple pores, i.e. a more tortuous path. This phenomenon is illustrated in Figure 22. To alleviate this problem a fixed time interval (1 hour), as determined by the first step anodization study, is allotted for each step.

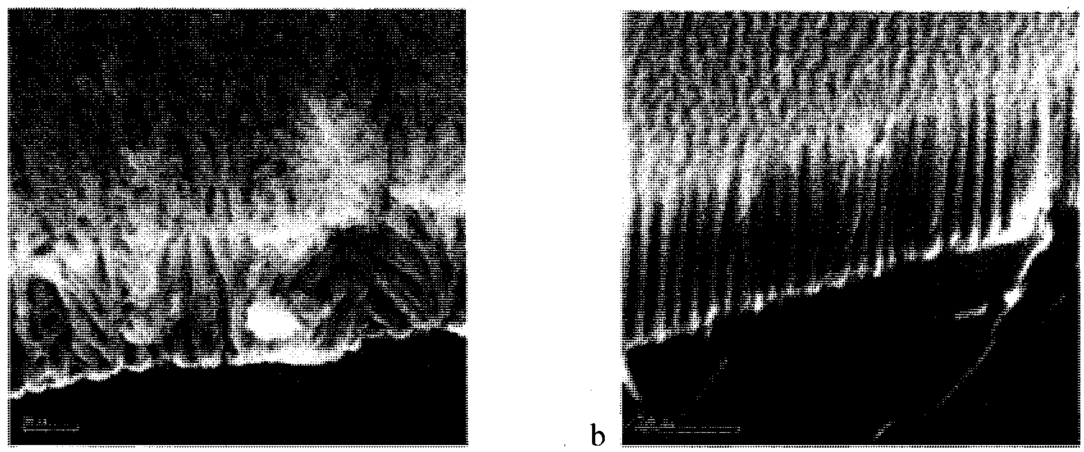
a b


Figure 22. Side profile of cleaved substrates. a) Incomplete etch time resulting in a high tortuosity value. b) Highly order pores with a tortuosity value close to 1.

The average tortuosity for each substrate was calculated and resultant values ranged from 1.069 to1.692. The high and low values reflect the results for substrates 4 and 7, respectively. A summary of all of the results is illustrated in Figure 23.

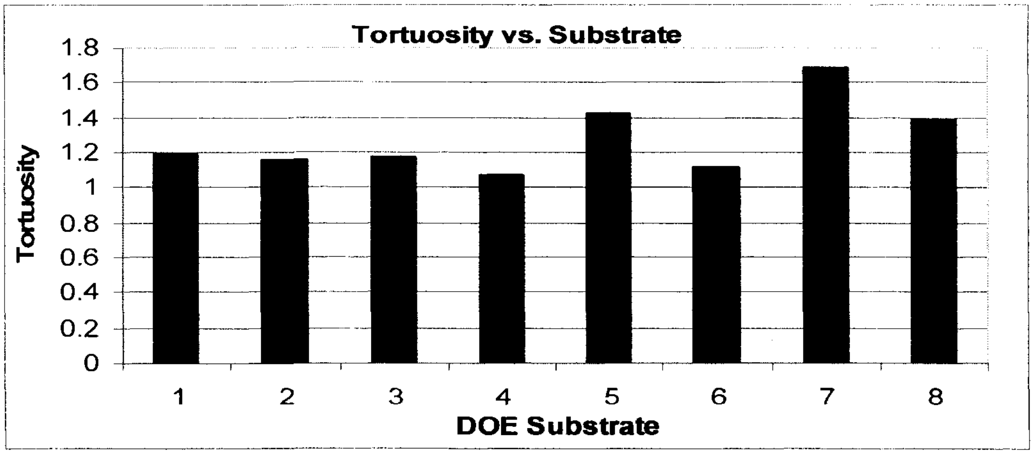


Figure 23. Summary of the tortuosity results for the DOE substrates.

The mean scores and factor effects for the DOE of the pore tortuosity were also calculated and are expressed in Table 8. However, this table uses pore length, not tortuosity to observe the effects. Tortuosity is a direct function of the pore length; the longer the average length, the higher the tortuosity value. The average pore lengths are used to demonstrate a more pronounced result on the effect scores.

Table 8. Summary of the DOE factor effects for pore length (tortuosity).

Run	Sample	COA	CPA	V	COA-CPA	COA-V	CPA-V	Length (nm)
1	1	-	-	+	+	-	-	582.480
2	1	-	-	-	+	+	+	568.032
3	1	-	+	+	-	-	+	589.535
4	1	-	+	-	-	+	-	530.380
5	1	+	-	+	-	+	-	715.740
6	1	+	-	-	-	-	+	557.386
7	1	+	+	+	+	+	+	850.080
8	1	+	+	-	+	-	-	710.228
Divisor		4	4	4	4	4	4	
Effects:		140.752	64.146	92.952	79.445	56.151	6.551	
Mean	637.983							

Parameters	Definition of Effects		
	-	+	Units
Conc. oxalic acid (COA)	0.1	0.7	Moles/Liter
Conc. H_3PO_4 (CPA)	0.2	0.6	Moles/Liter
Voltage (V)	30	50	Volts

From Table 8 it is evident that the concentration of the oxalic acid and voltage have the greatest effect on the pore length; the voltage increases the average pore length by almost 93 nanometers. No such statement can be made of the concentration of oxalic acid due to the strong interaction with phosphoric acid. However, a high concentration of oxalic acid (0.7 M) combined with the low concentration of phosphoric (0.2 M) acid results in longer nanopore values and the converse is true for short nanopore lengths (0.1 M oxalic acid and 0.4 M phosphoric acid).

The response factors for the acid electrolyte solutions and voltages versus nanopore length were also calculated and the resultant plots are shown in Figures 24, 25 and 26.

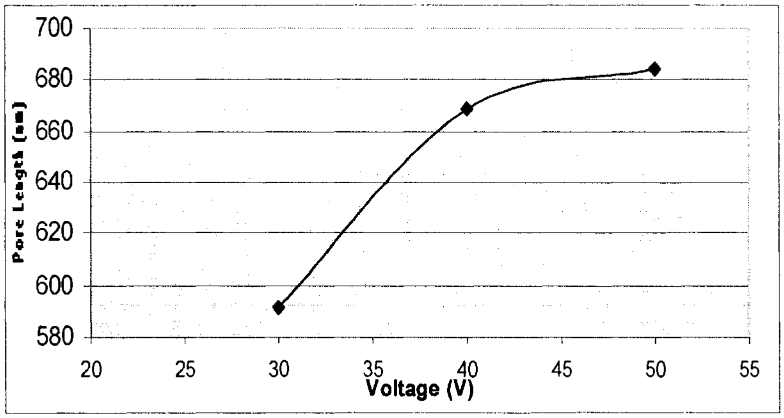


Figure 24. Response factor for voltage versus mean pore length.

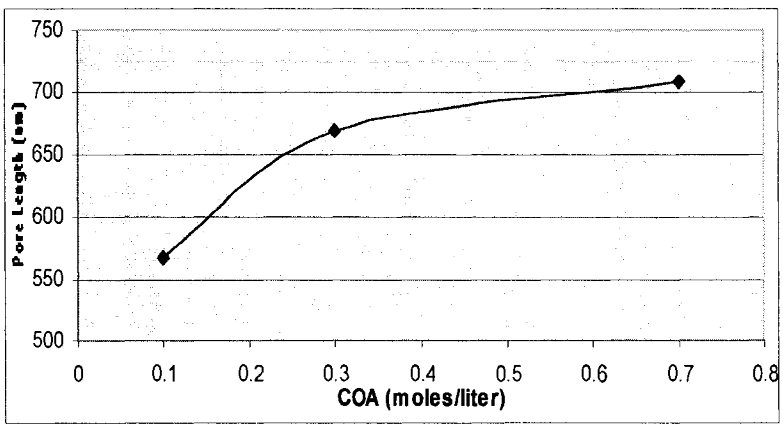


Figure 25. Response factor for concentration of oxalic acid and nanopore length.

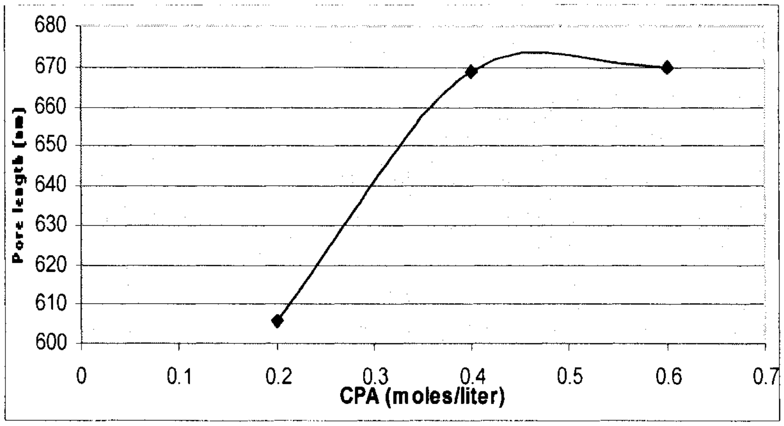


Figure 26. Response factor for phosphoric acid concentration and pore length.

From the response factor plots it is demonstrated that to obtain a shorter overall nanopore length a low voltage and low acid electrolyte solutions should be employed. Conversely, to attain an overall morphology of a longer nanopore length, the reverse is true.

The lower voltage setting (30 V) results in an average nanopore length of 591.51 nm, whereas the higher setting (50 V) results in a mean value of 684.46 nanometers. This is the expected observation; the higher voltage setting increases the reaction rate and thus allows for a more appreciable rate of penetration of the acids into the aluminum layer, whereas the lower setting results in a slower reaction rate and produces a nanopore that is 13.58 % shallower than the higher setting.

The acid electrolyte solutions also follow the expected results. The oxalic acid concentration of 0.1M produced and average pore length of 567.61 nm, while the 0.7 M solution yielded a mean pore length of 708.35 nm (a difference of 19.87 %). The phosphoric acid concentrations of 0.2M and 0.6M resulted in a mean nanopore length of

605.91 nm and 670.04 nm, respectively. The higher oxalic acid concentration also assists in increasing the reaction rate and contributes to the alleviation of any barrier type film that may form during the anodization process. The increased hydrogen ion presence increases the rate of attack at the oxide/electrolyte interface and thus lengthens the nanopores. The lower phosphoric acid concentration resulted in a 9.57 % shallower pore. This is the lowest observed difference of the three factors and may be due to a very thin or non-existent barrier type film. During the etching process the elevated phosphoric acid concentration better removes any barrier type film and consequently contributes to an overall nanopore length increase, however, if this film is very minimal or entirely not present the change in acid concentration may not have as significant of an effect.

5.2 Interaction Effects

The effects of each variable can be assessed by calculating the scores of each DOE matrix; however this method only describes the large overall effects and does not establish criterion for interaction effects. When interaction effects are observed for each DOE matrix they can help identify if any one variable is interacting with another to the extent that it may be altering the observed results. In essence, the effect is modified (qualified) by another effect.

5.2.1 Interaction Effects for Table 6 - Diameter

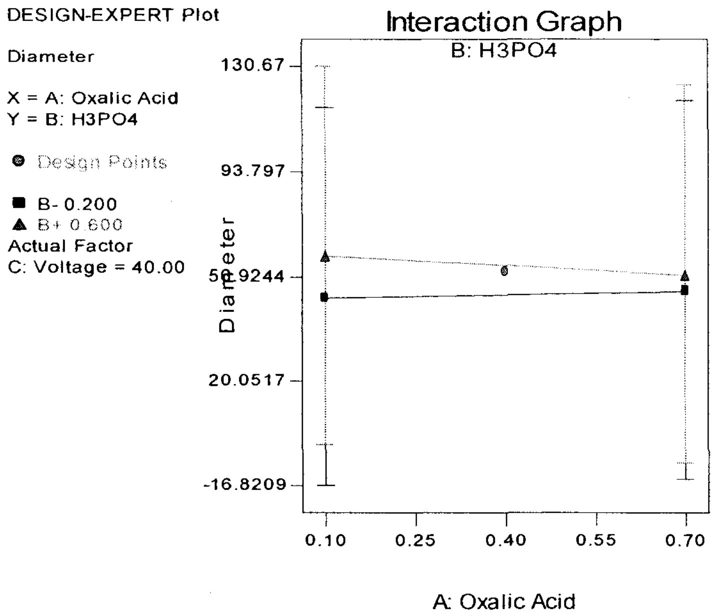


Figure 27. Interaction plot of oxalic and phosphoric acids for pore diameter.

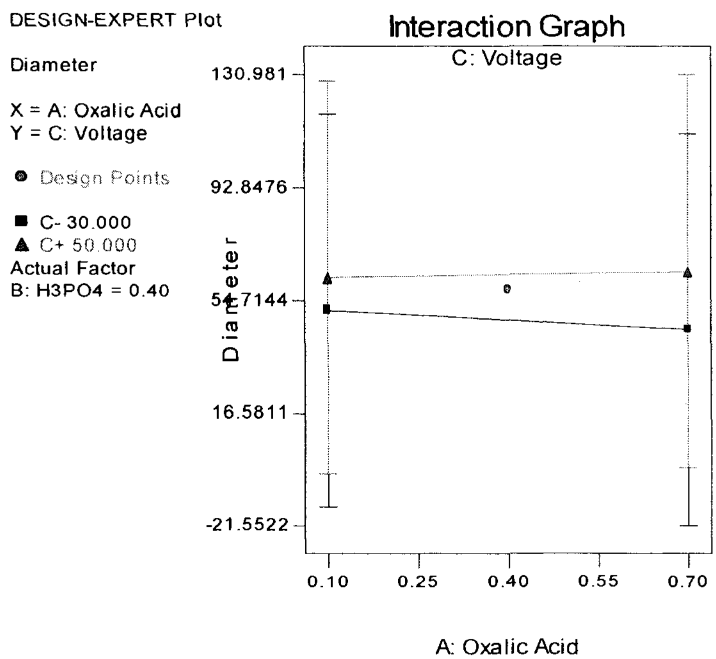


Figure 28. Interaction plot for voltage and oxalic acid for pore diameter.

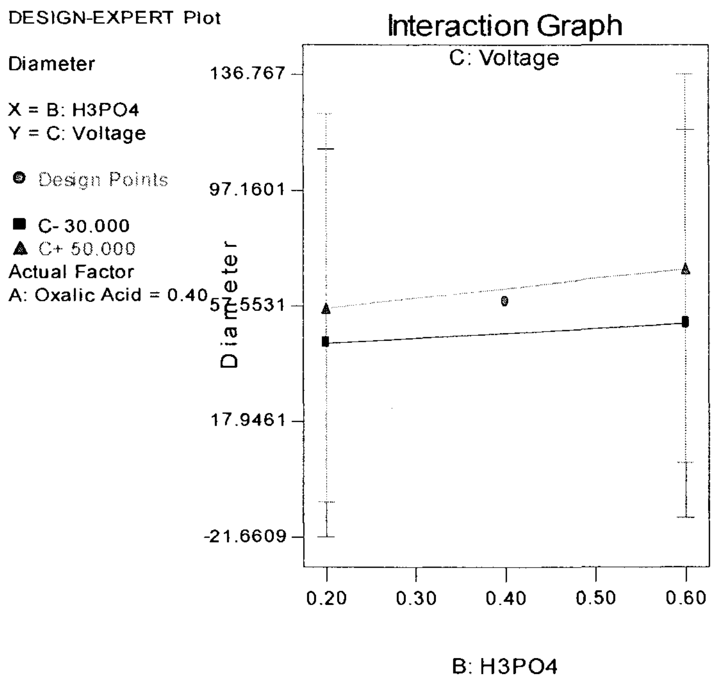


Figure 29. Interaction plot of voltage and phosphoric acids for pore diameter.

The interaction plots, Figures 27, 28, and 29 clearly demonstrate that there are no significant interactions occurring, in the ranges studied, between the three variables that affect the nanopore diameter. Each variable is separately scored in the DOE matrix, because there are no interaction effects, the individual scores are scrutinized without any concern of one or more of the other variables affecting the resultant scores.

5.2.2 Interaction Effects for Table 7 – Nanopore Density

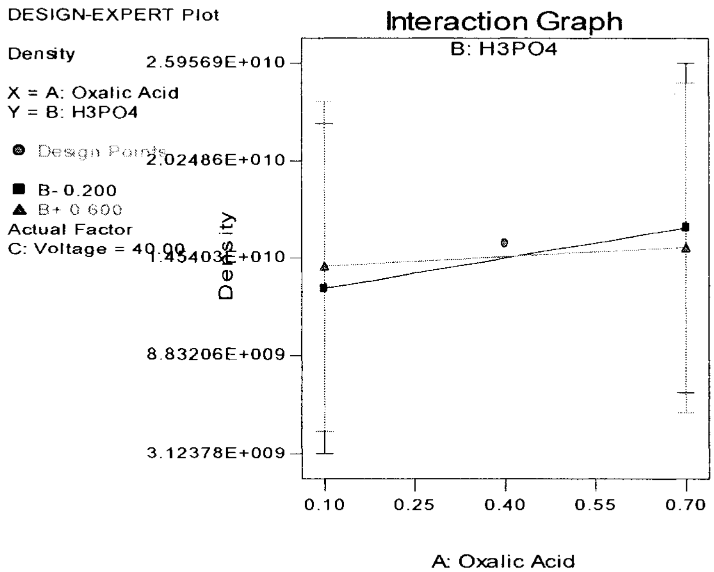


Figure 30. Interaction plot of oxalic acid and phosphoric acids for pore density.

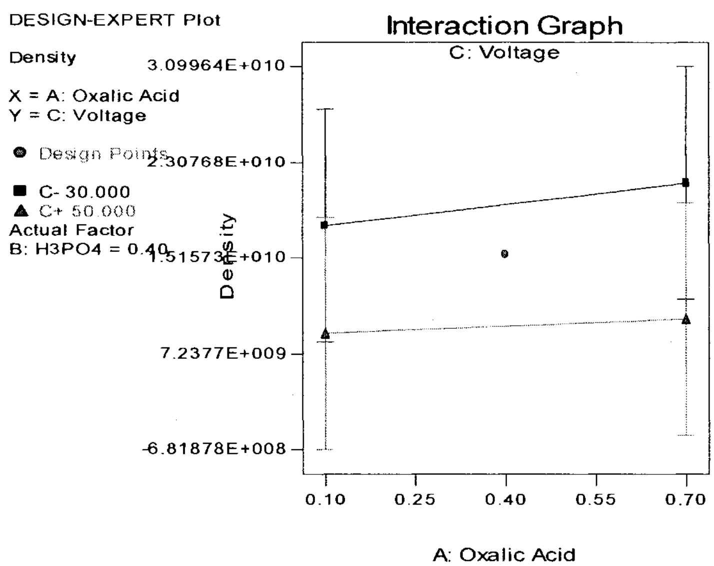


Figure 31. Interaction plot of oxalic acid and voltage for pore density.

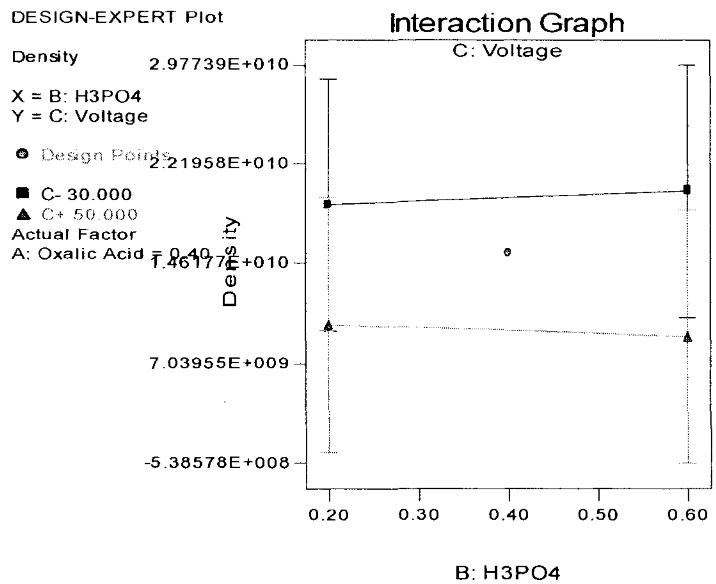


Figure 32. Interaction plot of phosphoric acid and voltage for pore density.

From the interaction graph, Figure 30, it is apparent that there is a strong interaction influence on pore density between the phosphoric and oxalic acid concentrations. Due to this interaction effect no statement about the DOE score can be made separately about the two electrolyte solutions. It is clearly demonstrated that the resultant scores for the solutions is not independent of one another. The interaction effects limit the examination of each factor; one factor affects the response differently depending on the value of another factor. The voltage, although it affects the pore density, does not have any significant interaction with the electrolyte solutions as illustrated by Figures 31 and 32.

5.2.3 Interaction Effects for Table 8 – Nanopore Length

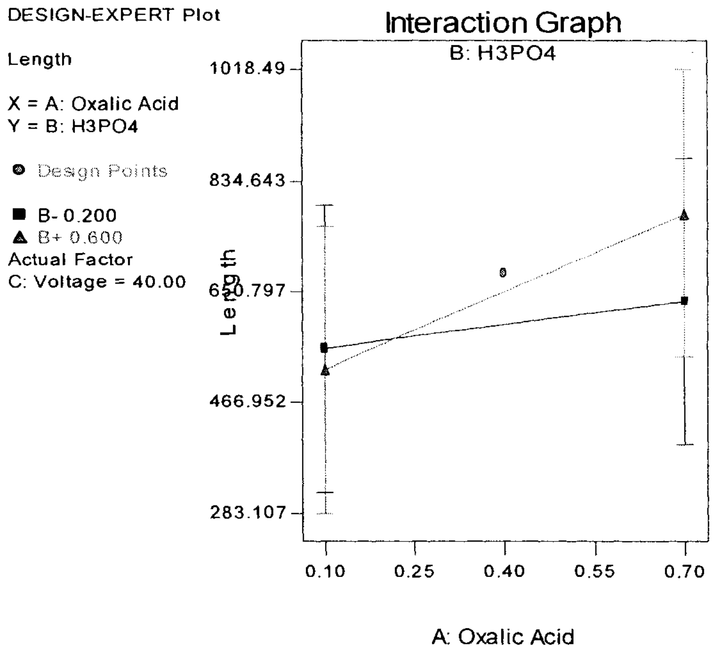


Figure 33. Interaction plot of phosphoric and oxalic acids for pore tortuosity.

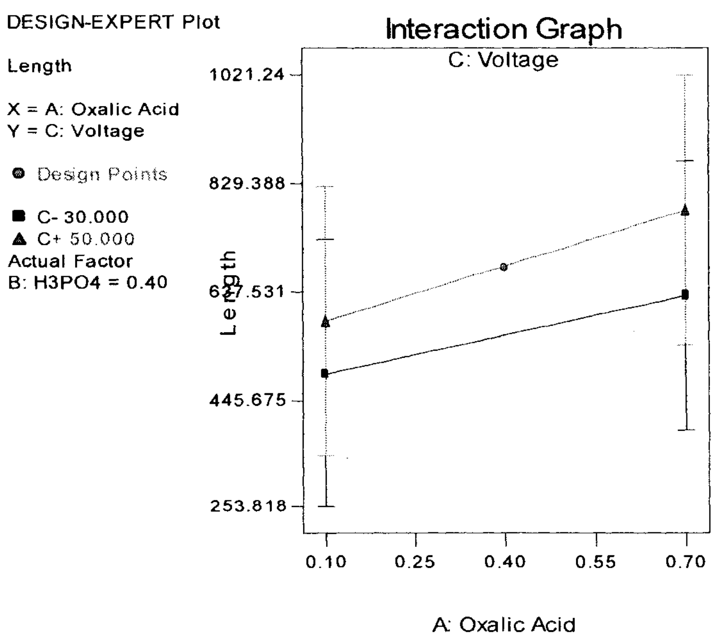


Figure 34. Interaction plot of voltage and oxalic acid for pore tortuosity.

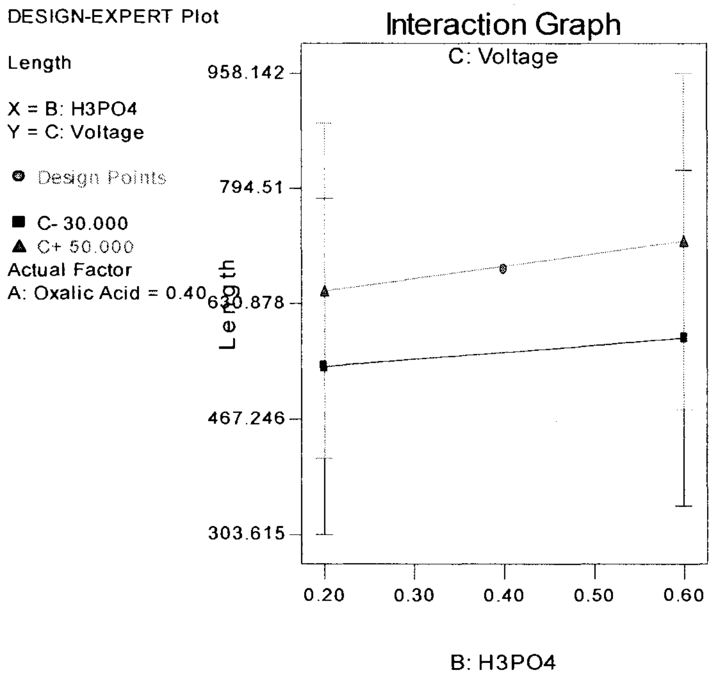


Figure 35. Interaction plot of voltage and phosphoric acid for pore tortuosity.

For pore tortuosity the only interaction effects occurring are between the phosphoric and oxalic acids; the acids do not interact with the voltage conditions. These interactions are illustrated in Figures 33, 34, and 35. As mentioned for the prior interaction effects analysis; the interaction affects of the electrolyte solutions requires that their individual DOE scores be nullified. The two scores cannot be observed as mutually exclusive.

5.3 Statistical Analysis

Each substrate was evaluated for the resultant nanopore density, tortuosity, and diameters resulting from the DOE conditions. A summary of the results for each substrate is provided in Table 9.

Table 9. Summary of results for density, tortuosity, and diameter for each substrate.

Substrate	**Location**	**Mean Diameter (nm)**	**Density (pore/cm2)**	**Location**	**Total Pore Length (nm)**	**Mean Pore Length (nm)**	**Tortuosity**
1	Edge	52.07	1.02e+10	Edge	8954.12	559.63	
	Edge	48.77	8.64e+09	Edge	5363.09	536.3	
	Ring	42.33	8.38e+09	Edge	15108.59	629.52	
	Middle	55.76	1.00e+10	Edge	20654.1	604.47	
Mean of means		49.73	9.32e+09		50079.9	582.48	1.19
2	Edge	50.81	1.38e+10	Edge	27800.64	617.97	
	Middle	51.35	1.62e+10	Edge	12758.15	579.92	
	Edge	45.01	1.85e+10	Edge	9808.955	544.942	
	Edge	50.56	1.62e+10	Edge	10585.93	529.2964	
Mean of means		49.43	1.62e+10		60953.675	568.0321	1.16
3							
	Middle	81.56	8.01e+09	Edge	14535.35	581.41	
	Middle	80.50	8.19e+09	Edge	12445.9	565.72	
	Edge	72.08	8.51e+09	Edge	22381.05	588.98	
	Edge	67.00	9.92e+09	Edge	8086.35	622.03	
Mean of means		75.29	8.66e+09		57448.65	589.535	1.17
Substrate	**Location**	**Mean Diameter (nm)**	**Density (pore/cm2)**	**Location**	**Total Pore Length (nm)**	**Mean Pore Length (nm)**	**Tortuosity**
4	Middle	60.70	2.02e+10	Edge	18677.2	565.975	
	Edge	54.46	1.76e+10	Edge	13531.2	520.4308	
	Middle	54.29	1.97e+10	Edge	9782.942	514.8917	
	Edge	43.14	2.11e+10	Edge	10404.48	520.2239	
Mean of means		53.15	1.97e+10		52395.822	530.38035	1.07

Table 9 Continued. Summary of results for density, tortuosity, and diameter for each substrate.

Substrate	Location	Mean Diameter (nm)	Density (pore/cm2)	Location	Total Pore Length (nm)	Mean Pore Length (nm)	Tortuosity
5	Edge	71.69	1.03e+10	Edge	16929.12	705.38	
	Middle	67.90	1.03e+10	Edge	15093.23	754.66	
	Edge	58.37	1.04e+10	Edge	14956	712.19	
	Middle	56.89	1.16e+10	Edge	26938.38	690.73	
Mean of means		63.71	1.07e+10		73916.73	715.74	1.42
6	Edge	37.90	2.66e+10	Edge	20101.43	503.54	
	Middle	41.07	1.97e+10	Edge	16952.31	565.07	
	Edge	39.88	2.07e+10	Edge	17490.46	647.79	
	Middle	41.36	2.10e+10	Edge	6157.733	513.1444	
Mean of means		40.05	2.20e+10		60701.933	557.3861	1.11
7	Edge	68.37	9.18e+09	Edge	32100.59	823.09	
	Middle	66.71	9.25e+09	Edge	37099.65	843.17	
	Edge	64.38	1.10e+10	Edge	20548.31	893.4	
	Edge	61.91	9.02e+09	Edge	12609.9	840.66	
Mean of means		65.34	9.60e+09		102358.45	850.08	1.69
8							
	Middle	50.07	1.97e+10	Edge	22534.74	726.93	
	Edge	54.98	1.85e+10	Edge	17834.46	743.1	
	Edge	46.23	2.11e+10	Edge	14754.8	776.57	
	Ring	47.72	2.36e+10	Edge	23178.25	594.31	
Mean of means		49.75	2.07e+10		78302.25	710.2275	1.39

The values used to determine the mean diameter for each substrate observe a normal distribution. This characteristic shape is indicative of all of the substrate histograms. Figures 36 and 37 illustrate this point.

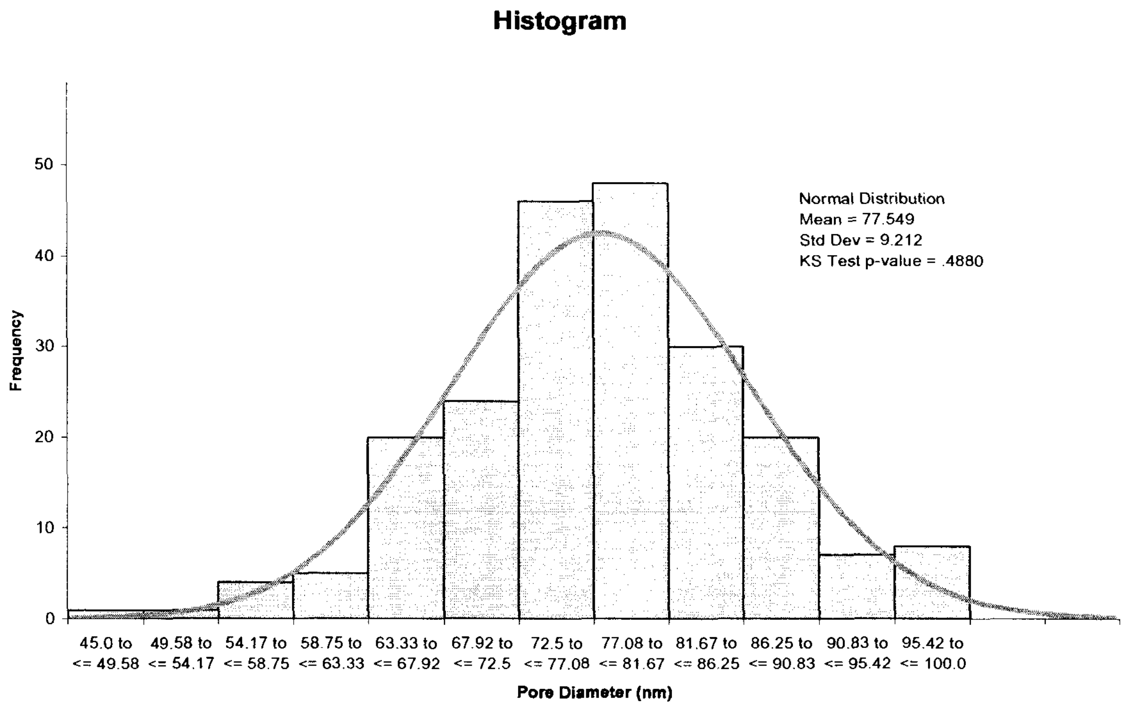


Figure 36. Histogram of pore diameter for substrate 3.

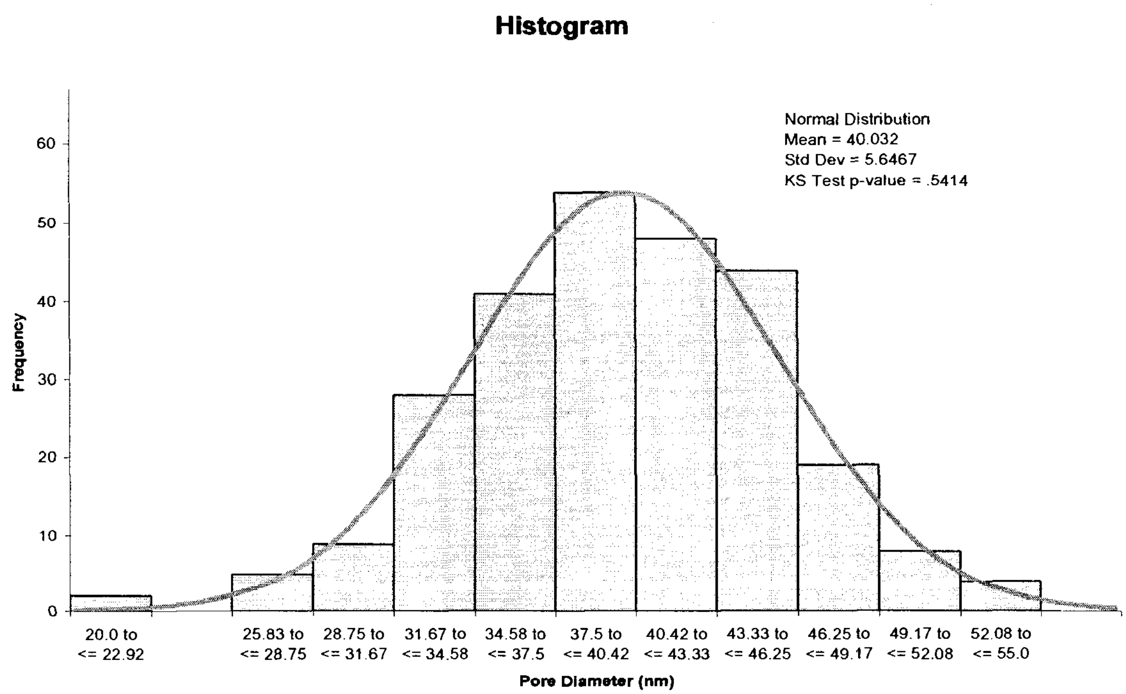


Figure 37. Histogram of pore diameter for substrate 6.

The histograms provided illustrate the normal distributions of the nanopore diameter measurements. Substrates 3 and 6 were chosen because they represent the smallest (40.05 nm) and largest mean diameters (75.29 nm), respectively. The Gaussian distributions imply randomness and substantiate the results.

Histograms were also plotted for the nanopore lengths. Figures 38 and 39 contain the plots for the two extreme mean values for tortuosity, 1.07 for substrate 4 and 1.69 for substrate 7. These histograms are not truly Gaussian.

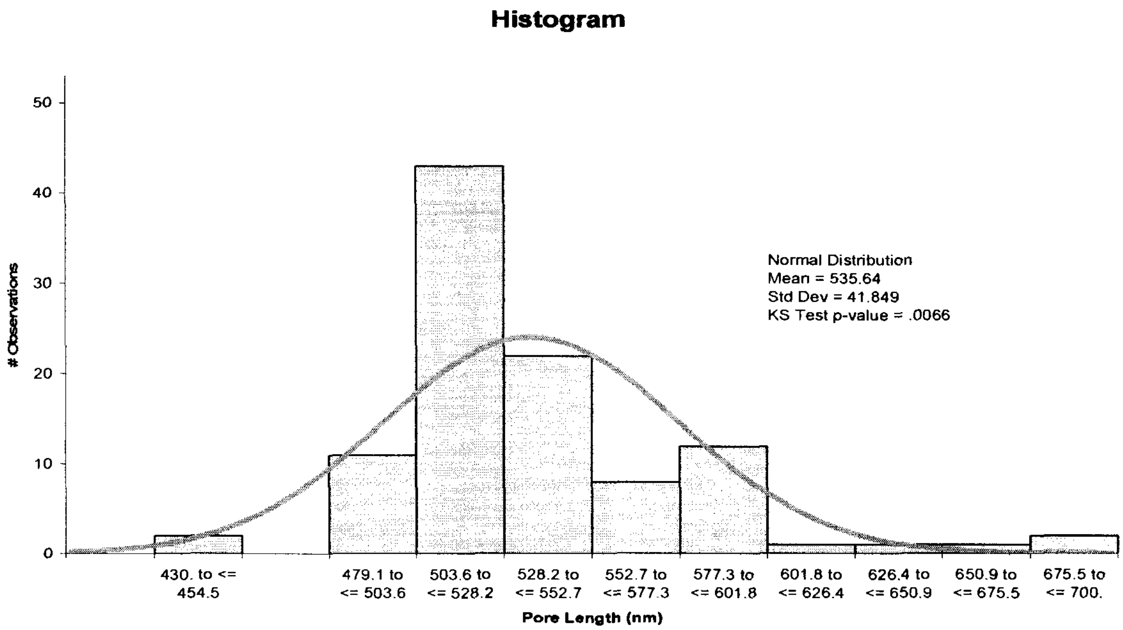


Figure 38. Histogram for the pore length distribution for substrate 4.

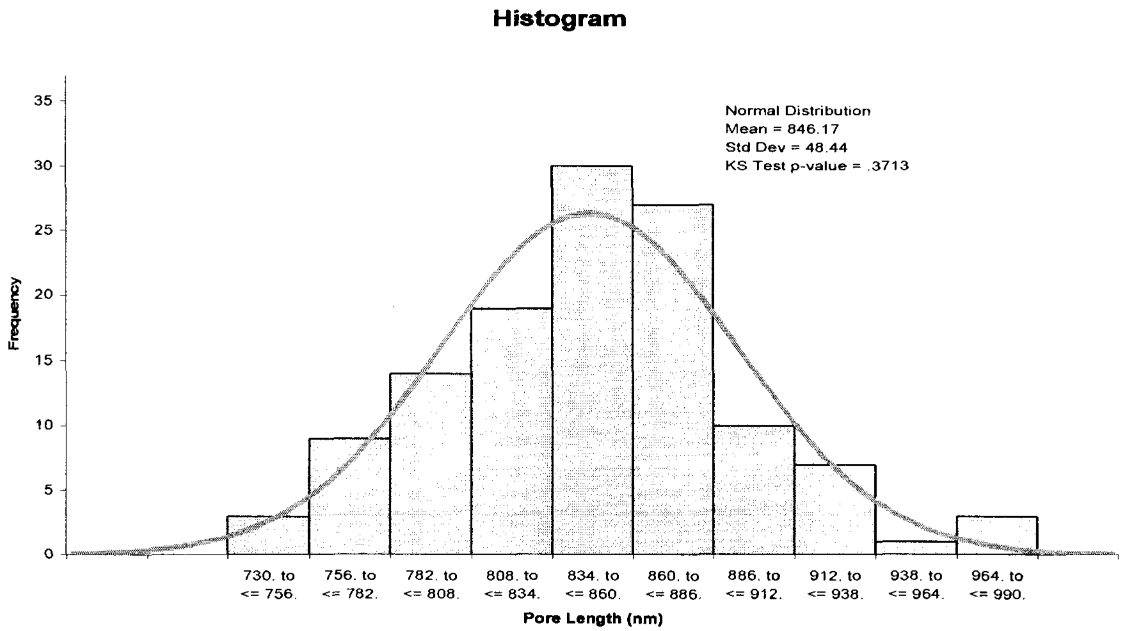


Figure 39. Histogram for the pore length distribution for substrate 7.

These distributions follow the same normal distribution pattern as stated for the diameter analysis. They show good distribution and provide an illustration of the typical results for all of the nanopore length histograms.

5.4 Temperature Study

The effect of temperature on pore tortuosity, diameter, and density was studied independent of the DOE. The three temperatures explored were 0°C, 22°C, and 48°C with a tolerance of ± 5°C. The results for the experiments are summarized in Table 10 and SEM images are provided in Figure 40.

Table 10. Summary of results for temperature study.

Run	Average Diameter (nm)	Density (pores/cm2)	Tortuosity
0 Degree Run	36.87	3.14e+10	1.10
22 Degree Run	58.74	1.54e+10	1.34
48 Degree Run	N/A	N/A	N/A

The results of the temperature study show that at a low temperature (0°C) the pore diameter is significantly smaller, but the tortuosity value is much closer to the preferred value of one. At an elevated temperature (22°C) the pore diameter increases however, the tortuosity value is considerably affected in a negative manner. The pore density is noticeably smaller at a higher temperature value versus a lower temperature, as would be expected; the larger pore diameters allow for fewer pores to exist at the increased temperature. The standard deviations are as follows: 15.47 nm, 1.13 e^{+10} pores, and 0.186 for the diameter, density, and tortuosity, respectively. No data is available for the 48 degree run due to the film being completely destroyed at this temperature; the SEM images in Figure 41 exemplify the results. The experiment was repeated to substantiate the resultant effect.

The observed temperature effect may be due to the accelerated rate of reaction brought on by the increase in temperature. As the reaction proceeds the pores nucleate with adjacent pores and create larger pores and this process is repeated indefinitely until the reaction is stopped. With an elevated temperature this process may be dramatically increased and hence, result in the aluminum film being completely destroyed, i.e. the pores nucleate at such a pace that the whole aluminum surface is destroyed and not enough space remains to distinguish the nanopores.

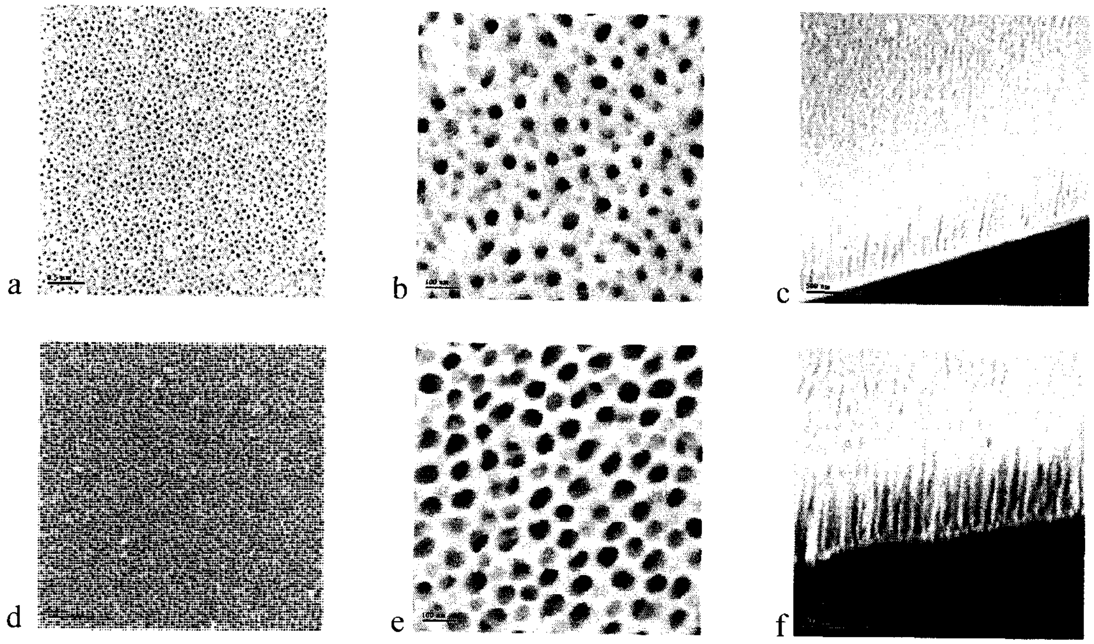


Figure 40. SEM images for the 0 degree temperature experiment: a) top view at 18 K magnification, b) Top view at 80 K magnification, and c) side view of pores at 25 K magnification. Images for 22 degree temperature experiment: d) top view at 15 K magnification, e) top view of pores at 80K magnification, and e) side view of nanopores at 35 K magnification.

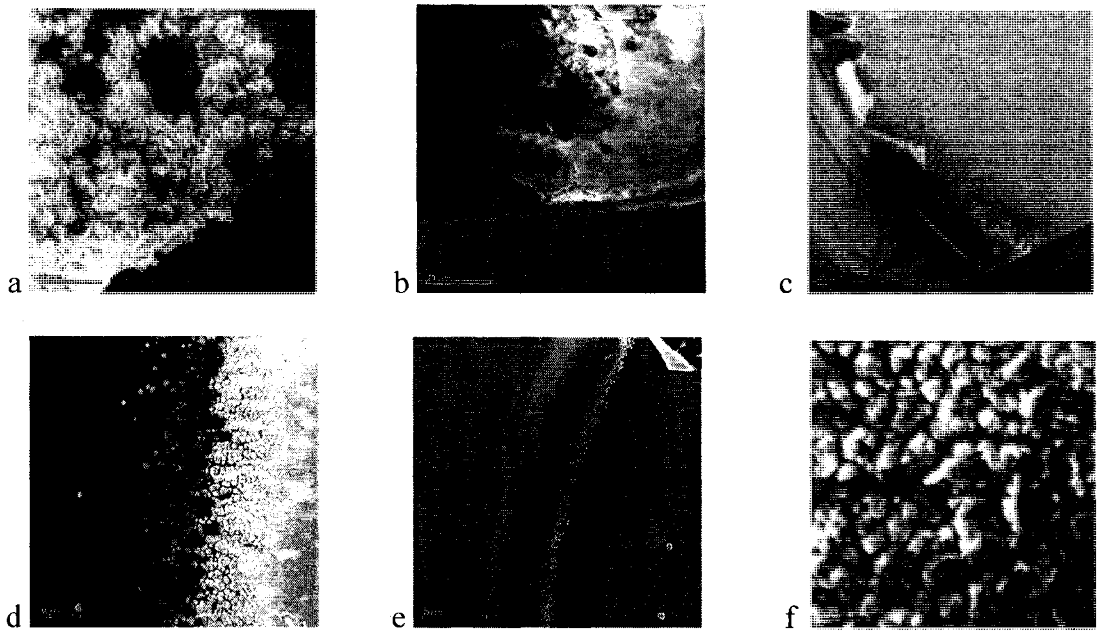


Figure 41. SEM images for the 48 degree temperature run. Experiment #1: a) top view of the first run at 300X magnification, b) side view at 300 X magnification, and c) top view of the outer ring at 30 X magnification. Experiment #2: a) Top view at 300 X, b) top view of the outer ring at 30 X, and c) destroyed aluminum surface at 600 X.

5.5 Experimental Controls

The experimental controls consisted of 3 center point runs scattered throughout the randomized experimental schedule as well as the anodization of substrates consisting solely of silicon and titanium. The latter experimental controls are provided to show that the anodization process was exclusive to the aluminum surface and did not continue into the actual silicon surface of the substrate.

Table 11 provides a summary of the results from the three center point runs. The results for nanopore diameter of the center point conditions have a standard deviation of 6.52 nm. The standard deviations for pore density and tortuosity are $9.46e^{+7}$ and 0.124, respectively. These values are all within 2 standard deviations of the averages.

Table 11. Summary of results for randomized center point experiments.

Run	Average Diameter (nm)	Density (pores/cm2)	Tortuosity
Center Point Run	65.99	1.11e+10	1.48
Repeatability Run	53.33	2.16e+10	1.29
Reproducibility Run	56.92	1.36e+10	1.26
Mean of mean	58.74 ± 3.08 nm	1.54e+10 ± 4.71e+7	1.34 ± 0.06

The results from the center point runs help in confirming the DOE matrix data. The two experiments that used the extreme conditions are as follows: Substrate 7; high phosphoric acid concentration (0.6 M), high oxalic acid concentration (0.7 M), and the high voltage setting (50 V). Substrate 2; the opposite extreme of low phosphoric acid concentration (0.2 M), low oxalic acid concentration (0.1 M), and the low voltage setting (30 V). When the mean nanopore characteristics of diameter, density, and tortuosity values of these two runs are compared with the center point condition experiments, the center point results lie in the middle of these two extremes. These results are summarized in Table 12.

Table 12. Summary of the center point, substrate 2, and substrate 7 results.

Substrate	Mean of Means Diameter (nm)	Mean of Means Density (pores/cm2)	Mean of Means Tortuosity
2	49.43	1.62e+10	1.16
Center Point	58.74	1.54e+10	1.34
7	65.34	9.60e+09	1.69

5.5.1 Silicon and Titanium Anodization

The SEM images for the anodization process for silicon and titanium reveal that there is no appreciable anodization occurring at either substrate surface. This suggests that the anodization process, by design, is impeded at the titanium façade. Figure 42 shows the SEM images for all of the results.

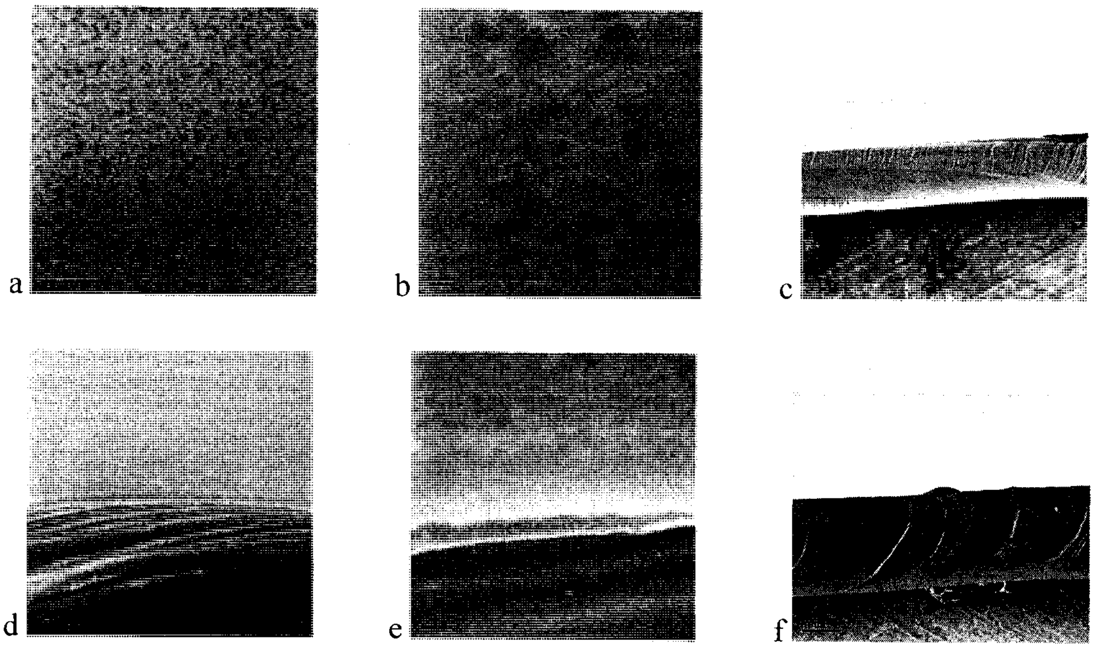


Figure 42. SEM images for the anodized silicon substrate: a) top view of the silicon surface at 7 K magnification, b) top view at 35 K magnification, and c) side profile of cleaved substrate at 45 X magnification. SEM images for the titanium substrate: d) cleaved substrate seen a 2 K magnification, e) cleaved substrate at 15 K, and f) cleaved substrate at 45 K.

5.6 Pore Diameter as a Function of Grain Size

The nanopore dimensions are influenced by many variables, one of which may be the initial grain size of the aluminum film. This aspect of the substrates was also explored. Atomic force microscopy (AFM) was utilized in determining the grain size of the sputtered aluminum films on the three center point runs (see Figures 43-45). A summary of the grain size versus nanopore diameter for each center point run is given in Table 13. Also see Figure 46 for a plot of these attributes.

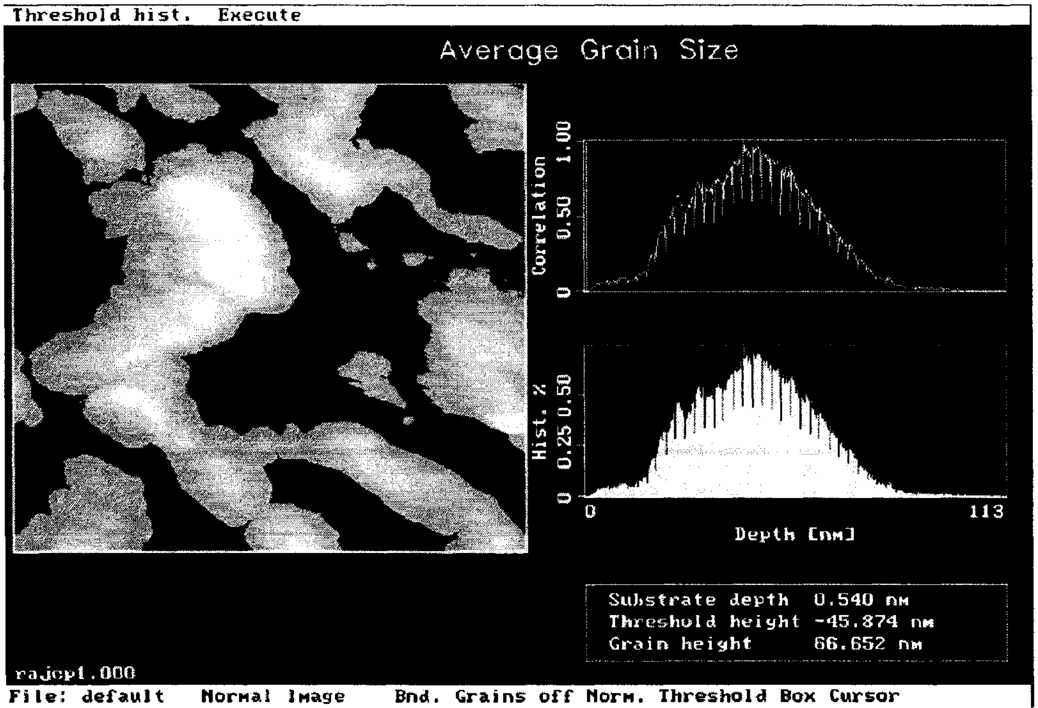


Figure 43. Grain size distribution for first center point run.

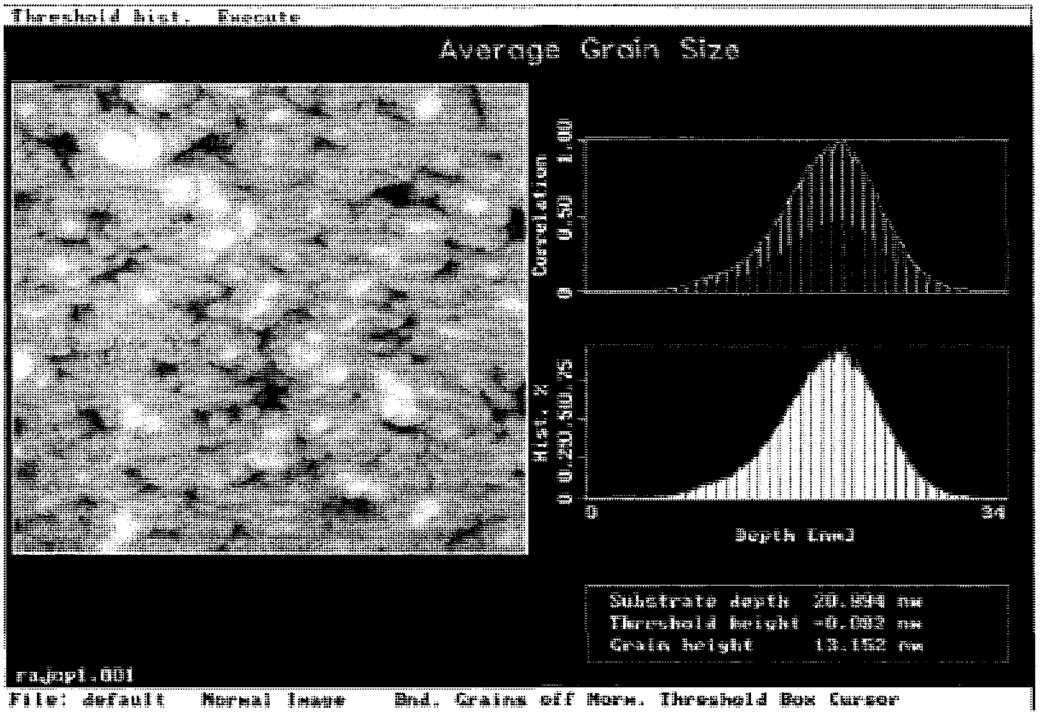


Figure 44. Grain size distribution for center point repeatability run.

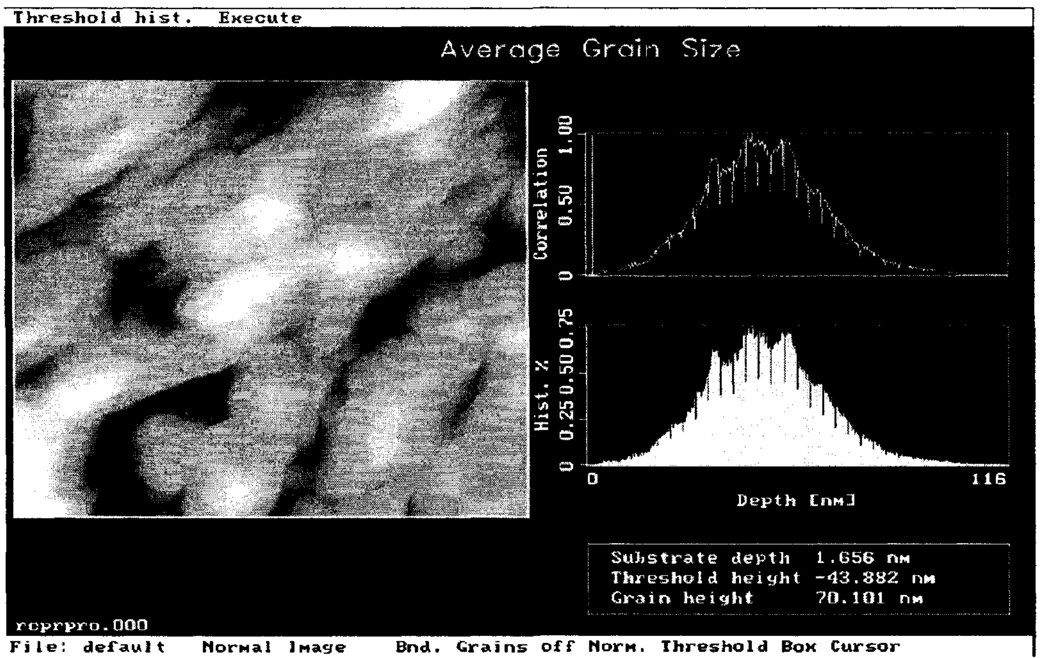


Figure 45. Grain size distribution for center point reproducibility run.

The sputtering process lead to variability in the aluminum grain size for all three substrates, however, for the first center point run and the center point reproducibility run it was more similar. The grain size for the center point repeatability run was considerably smaller. When comparing the nanopore diameter and tortuosity values for all three substrates, it is apparent that these values are reasonably similar. This implies that the nanopore dimensions are not as strongly influenced by the grain size and that the other variables (voltage and acid electrolyte concentrations) have a much greater impact on these characteristics. The grain size may initially impact the size and depth of the pores, but as the anodization process proceeds and pore nucleation increases, the overall influence of initial grain size is substantially diminished.

In a similar study by *Cai* et al., grain size versus pore size was evaluated. Their work observed the grain size on two separate surfaces. Anodic aluminum oxide thin films were deposited on both Si and SiO_2 surfaces. They concluded that the minimum pore size is determined by the anodization conditions and that the pore size can be adjusted by the pore-enlarging etching process. Also, they mentioned that the larger grain size of the starting aluminum films favors longer hexagonally ordered domains. This observation coincides with their annealed and electrochemically polished samples. Their work also supports my observations that the aluminum grain size does not necessarily influence the size of the nanopores.

Table 13. Summery of grain size and nanopore tortuosity and diameters.

Run	Nanopore Diameter (nm)	Tortuosity	Grain Size (nm)
Center Point Run	65.99	1.48	66.65
Repeatability Run	53.33	1.29	13.15
Reproducibility Run	56.92	1.26	70.10

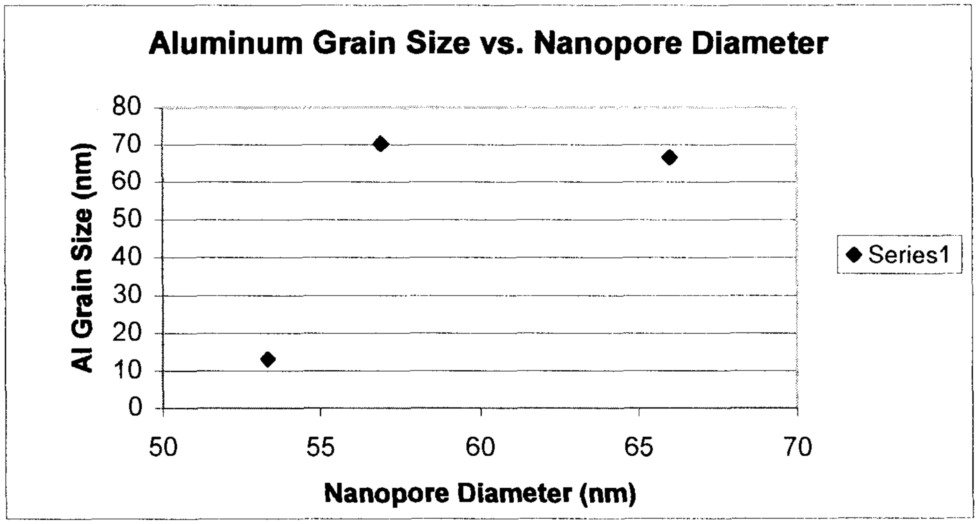


Figure 46. Plot of nanopore diameter versus grain size.

6.0 CONCLUSIONS

Aluminum thin film was deposited, via sputtering, on silicon substrates. These substrates were then exposed to an electrochemical anodization process with generates highly ordered nanopores in the aluminum film. The effects of varying the acid electrolyte concentrations (oxalic and phosphoric) and voltage on pore diameter, density, and tortuosity were studied. A two level, 2^3 factorial design of experiments scheme was utilized to compare how simultaneously altering all three variables affected the outcome of the desired characteristics at each condition. A subsequent, but separate, temperature study was also completed to consider the affects of temperature. A scanning electron microscope was employed to capture top and side profile images of the resultant substrates. Side profiles were revealed by cleaving each substrate all the way through the anodized area. Metric Plus software was used to analyze the captured images and calculate mean diameter, density, and tortuosity values.

The established range for the nanopore diameters is from 50-100 nanometers. This research work concludes that the voltage setting has the greatest effect on this range. It was also concluded that the oxalic and phosphoric acid concentrations do not as appreciably influence the pore diameters and that there are no significant interaction affects occurring between either electrolyte solution or between the solutions and the voltage settings. Substrate 3 yielded the most desirable results with a mean diameter value of 75.29 nanometers.

The effects on pore density were also studied. It was found that voltage also influences the density more than the acid concentrations. In terms of density the voltage has an overall negative effect; in essence it decreases the density. This is an expected result, the higher the voltage, the greater the reaction rate and thus the greater rate of adjacent pore nucleation, hence, the larger the pore diameter and the lower overall pore density. The acid electrolyte solutions also affected the pore density; however, no such conclusion can be reached since there was a considerable interaction effect between the phosphoric and oxalic acid concentrations.

From the DOE effects results it can be concluded that the tortuosity value is most influenced by the concentration of oxalic acid as well as the voltage. However, the oxalic acid has a large interaction effect with the phosphoric acid concentration; therefore, such a conclusion is invalidated. The voltage does not have any appreciable interaction effects and also yields the highest DOE effects value, and thus, has the greatest influence on tortuosity. The conditions for substrate 4 yielded the best results with tortuosity value of 1.07.

The separate temperature study revealed that at a reduced temperature (0°C) the average diameter was significantly reduced, however, the density and tortuosity were not as drastically altered. At a higher temperature (48°C) the film was completely destroyed. This phenomenon may be attributed to the reaction rate being increased and thus, a much higher rate of pore nucleation. Possibly enough adjacent pores nucleated to destroy the film completely.

The sputtered aluminum grain size for each controlled center point run was compared to the tortuosity and nanopore diameter values. The resultant anodized nanopore dimensions for each of these three substrates were very similar, yet the grain size varied for each substrate. This illustrates that the initial grain size of the film does not influence the nanopore diameter or length as appreciably as the voltage setting and acid electrolyte solution concentrations.

These results clearly demonstrate that all of the variables studied affect the pore diameter, density, and tortuosity. However, the affect of voltage on these characteristics is of greater significance. This study was based on concurrently exploring the affects of only three variables and temperature. Furthermore, to better understand the overall anodization process, which is shaped by many factors, further studies are required. This study provides a basis for manipulating nanopore diameters, density, and tortuosity to desired dimensions based on the required application.

7.0 FUTURE WORK

From this study some important results are observed and at the same time some imperative questions are raised. To gain a more complete understanding of the anodization process a study of aluminum thin film grain size and how it pertains to the size of the anodized pores would be very beneficial. A dedicated sputter combined with AFM and SEM surface characterization of pre and post anodization need to be utilized. Another body of work that attracts consideration is possibly to observe and measure the kinetics in terms of the rate of reaction. This process could be examined by varying the time intervals of each anodization step and measuring the number of pores observed. Hence a more complete or perhaps an equation for reaction rate could be determined.

An unexplained phenomenon appeared in the response factor correlating phosphoric acid concentration and nanopore density; the concentration had a maximum. This strange behavior was unexpected and warrants further investigation.

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Appendix A. List of Reagents and Equipment

LIST OF REAGENTS

Reagent	Supplier	Lot #
Oxalic Acid	Sigma	21K3644
Phosphoric Acid (85 %)	Aldrich	06427HR
Hydrofluoric Acid (48 %)	Aldrich	08972AU
Aluminum Target (99.999 %)	Alfa Aeser	A27P32
Titanium Target	NASA Ames	Unknown

LIST OF EQUIPMENT

IBS/TM200S Ion Beam Sputter

Scanning Electron Microscope, Hitachi S-4000

Hewlett Packard E3612A DC Power Supply 0-60V, 0-5 Amps.

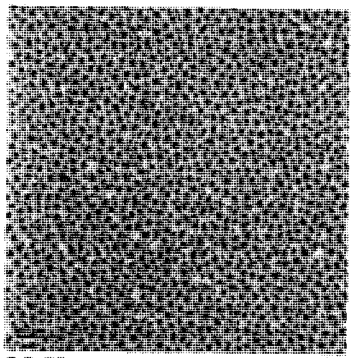
VWR Timer

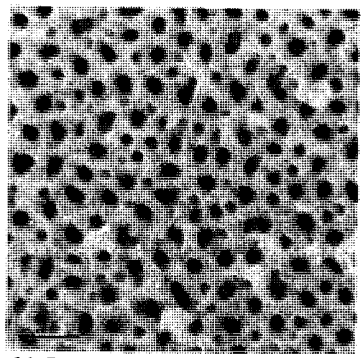
Crysteco Silicon Wafer 7036, n <111> As, 0.001 – 0.005 Ωcm

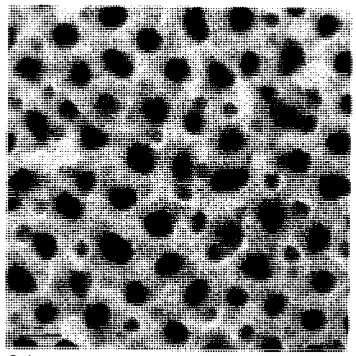
Water Pump

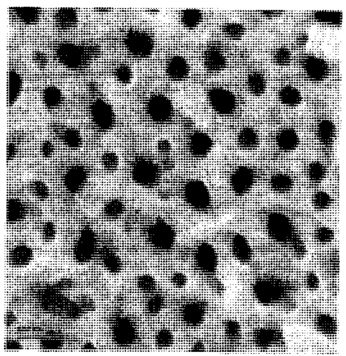
Appendix B. Substrate 1 Data

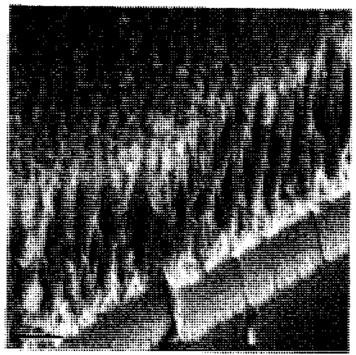
SEM Images for Substrate 1

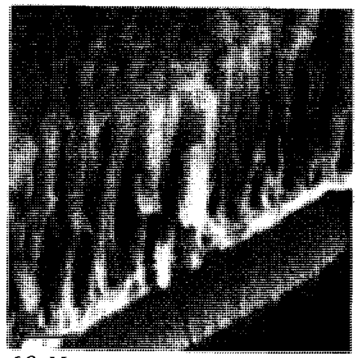

20 K
500 nm = 938 μm


60 K
200 nm = 1138 μm

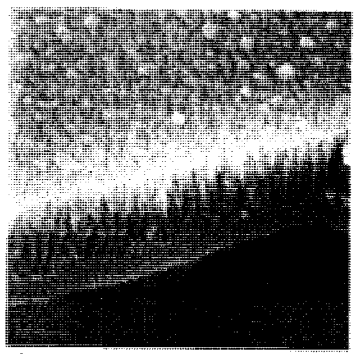

90 K
100 nm = 850 μm


100 K
100 nm = 938 μm


40 K
200 nm = 750 μm


60 K
200 nm = 1138 μm


25 K
500 nm = 1188 μm


20 K
500 nm = 938 μm

Diameter Measurements for Substrate1

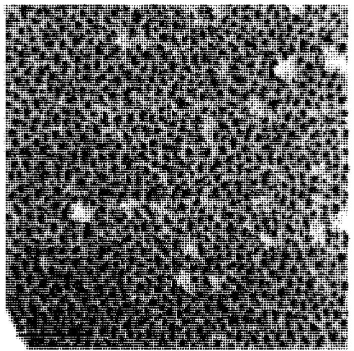
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	304	53.43	Diameter	440	51.76	Diameter	365	38.91
Diameter	332	58.35	Diameter	510	60.00	Diameter	316	33.69
Diameter	257	45.17	Diameter	444	52.24	Diameter	319	34.01
Diameter	348	61.16	Diameter	393	46.24	Diameter	341	36.35
Diameter	284	49.91	Diameter	375	44.12	Diameter	331	35.29
Diameter	266	46.75	Diameter	353	41.53	Diameter	316	33.69
Diameter	288	50.62	Diameter	378	44.47	Diameter	385	41.04
Diameter	319	56.06	Diameter	410	48.24	Diameter	466	49.68
Diameter	262	46.05	Diameter	416	48.94	Diameter	432	46.06
Diameter	289	50.79	Diameter	388	45.65	Diameter	391	41.68
Diameter	304	53.43	Diameter	452	53.18	Diameter	344	36.67
Diameter	302	53.08	Diameter	462	54.35	Diameter	348	37.10
Diameter	265	46.57	Diameter	377	44.35	Diameter	404	43.07
Diameter	273	47.98	Diameter	367	43.18	Diameter	413	44.03
Diameter	267	46.92	Diameter	402	47.29	Diameter	412	43.92
Diameter	274	48.15	Diameter	328	38.59	Diameter	422	44.99
Diameter	300	52.72	Diameter	358	42.12	Diameter	436	46.48
Diameter	313	55.01	Diameter	435	51.18	Diameter	440	46.91
Diameter	304	53.43	Diameter	346	40.71	Diameter	379	40.41
Diameter	312	54.83	Diameter	377	44.35	Diameter	409	43.60
Diameter	363	63.80	Diameter	456	53.65	Diameter	459	48.93
Diameter	315	55.36	Diameter	421	49.53	Diameter	400	42.64
Diameter	290	50.97	Diameter	424	49.88	Diameter	472	50.32
Diameter	273	47.98	Diameter	430	50.59	Diameter	358	38.17
Diameter	285	50.09	Diameter	518	60.94	Diameter	433	46.16
Diameter	310	54.48	Diameter	415	48.82	Diameter	361	38.49
Diameter	222	39.02	Diameter	394	46.35	Diameter	437	46.59
Diameter	317	55.71	Diameter	444	52.24	Diameter	476	50.75
Diameter	258	45.34	Diameter	362	42.59	Diameter	478	50.96
Diameter	90	47.97	Diameter	129	68.76	Diameter	112	59.70
Diameter	81	43.18	Diameter	88	46.91	Diameter	117	62.37
Diameter	101	53.84	Diameter	104	55.44	Diameter	98	52.24
Diameter	79	42.11	Diameter	103	54.90	Diameter	109	58.10
Diameter	108	57.57	Diameter	97	51.71	Diameter	115	61.30
Diameter	101	53.84	Diameter	114	60.77	Diameter	103	54.90
Diameter	100	53.30	Diameter	110	58.64	Diameter	95	50.64
Diameter	97	51.71	Diameter	92	49.04	Diameter	106	56.50
Diameter	103	54.90	Diameter	107	57.04	Diameter	129	68.76
Diameter	97	51.71	Diameter	91	48.51	Diameter	129	68.76
Diameter	97	51.71	Diameter	91	48.51	Diameter	129	68.76
Diameter	97	51.71	Diameter	91	48.51	Diameter	129	68.76
Diameter	97	51.71	Diameter	91	48.51	Diameter	129	68.76

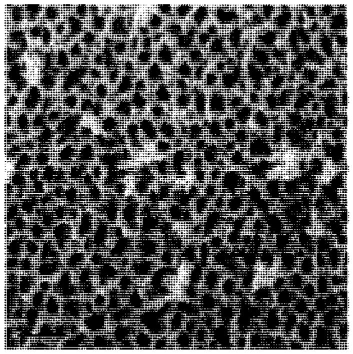
Diameter Measurements for Substrate1								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanome ters
Diameter	436	46.48	Diameter	88	46.91	Diameter	113	60.23
Diameter	440	46.91	Diameter	104	55.44	Diameter	118	62.90
Diameter	379	40.41	Diameter	103	54.90	Diameter	118	62.90
Diameter	409	43.60	Diameter	97	51.71	Diameter	116	61.83
Diameter	459	48.93	Diameter	114	60.77			
Diameter	400	42.64	Diameter	110	58.64			
Diameter	472	50.32	Diameter	92	49.04			
Diameter	358	38.17	Diameter	107	57.04			
Diameter	433	46.16	Diameter	106	56.50			
Diameter	361	38.49	Diameter	129	68.76			
Diameter	437	46.59	Diameter	101	53.84			
Diameter	476	50.75	Diameter	100	53.30			
Diameter	478	50.96	Diameter	91	48.51			
Diameter	380	40.51	Diameter	113	60.23			
Diameter	454	48.40	Diameter	113	60.23			
Diameter	429	45.74	Diameter	84	44.78			
Diameter	399	42.54	Diameter	106	56.50			
Diameter	381	40.62	Diameter	100	53.30			
Diameter	333	35.50	Diameter	104	55.44			
Diameter	348	37.10	Diameter	115	61.30			
Diameter	419	44.67	Diameter	91	48.51			
Diameter	391	41.68	Diameter	117	62.37			
Diameter	410	43.71	Diameter	109	58.10			
Diameter	90	47.97	Diameter	112	59.70			
Diameter	81	43.18	Diameter	91	48.51			
Diameter	101	53.84	Diameter	101	53.84			
Diameter	79	42.11	Diameter	99	52.77			
Diameter	108	57.57	Diameter	114	60.77			
Diameter	101	53.84	Diameter	103	54.90			
Diameter	100	53.30	Diameter	92	49.04			
Diameter	97	51.71	Diameter	92	49.04			
Diameter	103	54.90	Diameter	141	75.16			
Diameter	97	51.71	Diameter	88	46.91			
Diameter	91	48.51	Diameter	105	55.97			
Diameter	112	59.70	Diameter	126	67.16			
Diameter	117	62.37	Diameter	111	59.17			
Diameter	98	52.24	Diameter	119	63.43			
Diameter	109	58.10	Diameter	113	60.23			
Diameter	115	61.30	Diameter	106	56.50			
Diameter	103	54.90	Diameter	99	52.77			
Diameter	95	50.64	Diameter	98	52.24			
Diameter	129	68.76	Diameter	104	55.44			

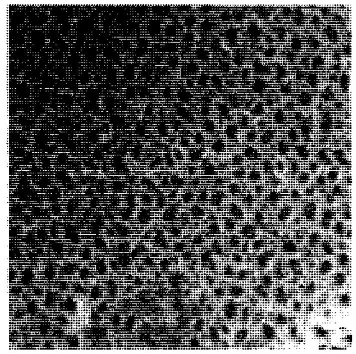
Nanopore Length Measurements for Substrate1					
Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	2644	622.12	Distance	1450	610.27
Distance	2420	569.41	Distance	1439	605.64
Distance	2263	532.47	Distance	1476	621.21
Distance	2579	606.82	Distance	1544	649.83
Distance	2520	592.94	Distance	1405	591.33
Distance	2438	573.65	Distance	1527	642.68
Distance	2182	513.41	Distance	1464	616.16
Distance	2076	488.47	Distance	1403	590.49
Distance	2313	544.24	Distance	1076	573.56
Distance	2700	635.29	Distance	976	520.26
Distance	2426	570.82	Distance	1063	566.63
Distance	2104	495.06	Distance	1038	553.30
Distance	2225	523.53	Distance	1047	558.10
Distance	2490	585.88	Distance	1116	594.88
Distance	2375	558.82	Distance	1051	560.23
Distance	2300	541.18	Distance	1059	564.50
Distance	2589	455.01	Distance	1103	587.95
Distance	2539	446.22	Distance	1139	607.14
Distance	3012	529.35	Distance	1063	566.63
Distance	3125	549.21	Distance	1075	573.03
Distance	3076	540.60	Distance	1118	595.95
Distance	3100	544.82	Distance	1127	600.75
Distance	2941	516.87	Distance	1088	579.96
Distance	3574	628.12	Distance	1163	619.94
Distance	3671	645.17	Distance	1166	621.54
Distance	2889	507.73	Distance	1213	646.59
Distance	1728	727.27	Distance	1188	633.26
Distance	1650	694.44	Distance	1126	600.21
Distance	1603	674.66	Distance	1214	647.12
Distance	1600	673.40	Distance	1163	619.94
Distance	1513	636.78	Distance	1191	634.86
Distance	1476	621.21	Distance	1100	586.35
Distance	1550	652.36	Distance	1189	633.80
Distance	1475	620.79	Distance	1141	608.21
Distance	1450	610.27	Distance	1163	619.94
Distance	1503	632.58	Distance	1175	626.33
Distance	1538	647.31	Distance	1126	600.21
Distance	1376	579.12	Distance	1314	700.43
Distance	1465	616.58	Distance	1276	680.17
Distance	1438	605.22	Distance	1153	614.61
Distance	1425	599.75	Distance	1329	708.42
Distance	1400	589.23	Distance	1218	649.25

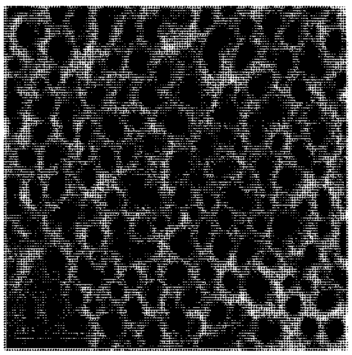
Appendix C. Substrate 2 Data

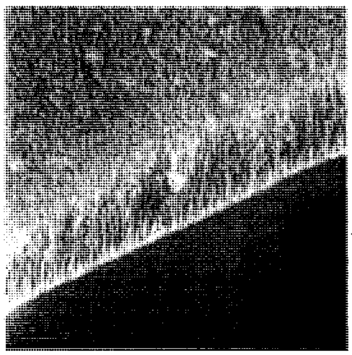
SEM Images for Substrate 2


30 K
500 nm = 1425 μm

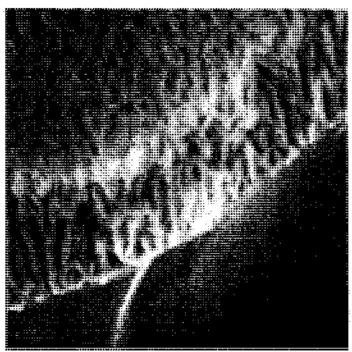

50 K
200 nm = 938 μm

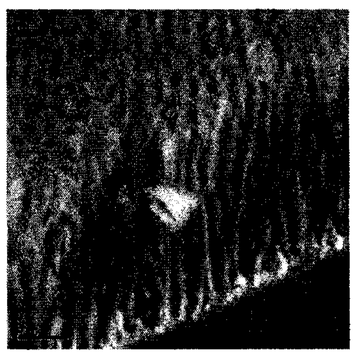

50 K
200 nm = 938 μm


70 K
200 nm = 1325 μm


20 K
500 nm = 928 μm


35 K
200 nm = 650 μm


50 K
200 nm = 938 μm


50 K
200 nm = 938 μm

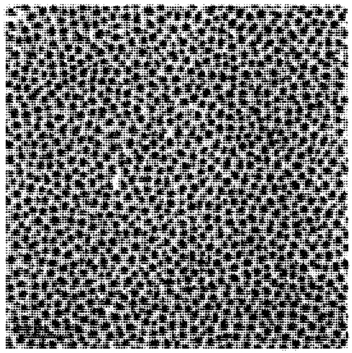
Diameter Measurements for Substrate 2								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	127	44.56	Diameter	144	50.53	Diameter	260	55.44
Diameter	91	31.93	Diameter	149	52.28	Diameter	219	46.70
Diameter	141	49.47	Diameter	114	40.00	Diameter	197	42.00
Diameter	100	35.09	Diameter	187	65.61	Diameter	266	56.72
Diameter	186	65.26	Diameter	146	51.23	Diameter	168	35.82
Diameter	174	61.05	Diameter	103	36.14	Diameter	159	33.90
Diameter	165	57.89	Diameter	132	46.32	Diameter	170	36.25
Diameter	98	34.39	Diameter	140	49.12	Diameter	223	47.55
Diameter	146	51.23	Diameter	165	57.89	Diameter	264	56.29
Diameter	124	43.51	Diameter	122	42.81	Diameter	269	57.36
Diameter	144	50.53	Diameter	161	56.49	Diameter	253	53.94
Diameter	126	44.21	Diameter	176	61.75	Diameter	221	47.12
Diameter	155	54.39	Diameter	189	66.32	Diameter	332	70.79
Diameter	119	41.75	Diameter	168	58.95	Diameter	290	61.83
Diameter	147	51.58	Diameter	171	60.00	Diameter	212	45.20
Diameter	146	51.23	Diameter	171	60.00	Diameter	323	68.87
Diameter	123	43.16	Diameter	190	66.67	Diameter	179	38.17
Diameter	148	51.93	Diameter	172	60.35	Diameter	303	64.61
Diameter	154	54.04	Diameter	135	47.37	Diameter	234	49.89
Diameter	116	40.70	Diameter	135	47.37	Diameter	246	52.45
Diameter	117	41.05	Diameter	172	60.35	Diameter	282	60.13
Diameter	143	50.18	Diameter	168	58.95	Diameter	243	51.81
Diameter	166	58.25	Diameter	172	60.35	Diameter	210	44.78
Diameter	160	56.14	Diameter	327	69.72	Diameter	180	38.38
Diameter	131	45.96	Diameter	175	37.31	Diameter	224	47.76
Diameter	119	41.75	Diameter	195	41.58	Diameter	402	85.71
Diameter	126	44.21	Diameter	204	43.50	Diameter	385	82.09
Diameter	127	44.56	Diameter	242	51.60	Diameter	204	43.50
Diameter	147	51.58	Diameter	245	52.24	Diameter	192	40.94
Diameter	129	45.26	Diameter	251	53.52	Diameter	254	54.16
Diameter	136	47.72	Diameter	213	45.42	Diameter	207	44.14
Diameter	185	64.91	Diameter	177	37.74	Diameter	172	36.67
Diameter	83	29.12	Diameter	193	41.15	Diameter	241	51.39
Diameter	126	44.21	Diameter	228	48.61	Diameter	269	57.36
Diameter	153	53.68	Diameter	293	62.47	Diameter	243	51.81
Diameter	171	60.00	Diameter	253	53.94	Diameter	232	49.47
Diameter	111	38.95	Diameter	260	55.44	Diameter	282	60.13
Diameter	149	52.28	Diameter	219	46.70	Diameter	304	64.82
Diameter	161	56.49	Diameter	271	57.78	Diameter	304	64.82
Diameter	145	50.88	Diameter	218	46.48	Diameter	232	49.47
Diameter	164	57.54	Diameter	231	49.25	Diameter	148	31.56
Diameter	151	52.98	Diameter	280	59.70	Diameter	163	34.75

Diameter Measurements for Substrate 2								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	261	55.65	Diameter	271	57.78	Diameter	383	57.81
Diameter	285	60.77	Diameter	212	45.20	Diameter	217	32.75
Diameter	238	50.75	Diameter	204	43.50	Diameter	295	44.53
Diameter	235	50.11	Diameter	241	51.39	Diameter	343	51.77
Diameter	176	37.53	Diameter	240	51.17	Diameter	305	46.04
Diameter	203	43.28	Diameter	190	40.51	Diameter	301	45.43
Diameter	226	48.19	Diameter	259	55.22	Diameter	367	55.40
Diameter	181	38.59	Diameter	218	46.48	Diameter	317	47.85
Diameter	187	39.87	Diameter	225	47.97	Diameter	301	45.43
Diameter	191	40.72	Diameter	185	39.45	Diameter	391	59.02
Diameter	145	30.92	Diameter	221	47.12	Diameter	194	29.28
Diameter	158	33.69	Diameter	194	41.36	Diameter	243	36.68
Diameter	190	40.51	Diameter	217	46.27	Diameter	368	55.55
Diameter	205	43.71	Diameter	175	37.31	Diameter	245	36.98
Diameter	237	50.53	Diameter	229	48.83	Diameter	330	49.81
Diameter	208	44.35	Diameter	212	45.20	Diameter	262	39.55
Diameter	222	47.33	Diameter	259	55.22	Diameter	295	44.53
Diameter	254	54.16	Diameter	210	44.78	Diameter	266	40.15
Diameter	212	45.20	Diameter	192	40.94	Diameter	286	43.17
Diameter	207	44.14	Diameter	200	42.64	Diameter	267	40.30
Diameter	207	44.14	Diameter	217	46.27	Diameter	293	44.23
Diameter	192	40.94	Diameter	182	38.81	Diameter	312	47.09
Diameter	198	42.22	Diameter	182	38.81	Diameter	438	66.11
Diameter	252	53.73	Diameter	212	45.20	Diameter	280	42.26
Diameter	179	38.17	Diameter	214	45.63	Diameter	394	59.47
Diameter	271	57.78	Diameter	207	44.14	Diameter	465	70.19
Diameter	174	37.10	Diameter	215	45.84	Diameter	426	64.30
Diameter	233	49.68	Diameter	390	58.87	Diameter	338	51.02
Diameter	185	39.45	Diameter	404	60.98	Diameter	277	41.81
Diameter	189	40.30	Diameter	356	53.74	Diameter	436	65.81
Diameter	197	42.00	Diameter	380	57.36	Diameter	265	40.00
Diameter	205	43.71	Diameter	261	39.40	Diameter	451	68.08
Diameter	257	54.80	Diameter	421	63.55	Diameter	290	43.77
Diameter	225	47.97	Diameter	421	63.55	Diameter	319	48.15
Diameter	199	42.43	Diameter	365	55.09	Diameter	326	49.21
Diameter	203	43.28	Diameter	358	54.04	Diameter	298	44.98
Diameter	215	45.84	Diameter	369	55.70	Diameter	228	34.42
Diameter	243	51.81	Diameter	235	35.47	Diameter	360	54.34
Diameter	188	40.09	Diameter	269	40.60	Diameter	338	51.02
Diameter	312	66.52	Diameter	498	75.17	Diameter	408	61.58
Diameter	229	48.83	Diameter	336	50.72	Diameter	285	43.02
Diameter	184	39.23	Diameter	354	53.43	Diameter	368	55.55

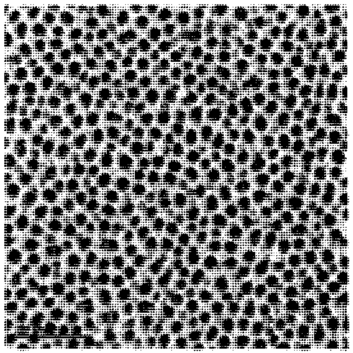
Nanopore Length Measurements for Substrate 2								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1276	680.17	Distance	1910	587.69	Distance	2849	607.46
Distance	1287	686.03	Distance	2005	616.92	Distance	2556	544.99
Distance	1792	955.22	Distance	1741	535.69	Distance	2355	502.13
Distance	1078	574.63	Distance	2102	646.77	Distance	2428	517.70
Distance	1065	567.70	Distance	2238	688.62	Distance	2570	547.97
Distance	1799	958.95	Distance	1936	595.69	Distance	2485	529.85
Distance	1246	664.20	Distance	1800	553.85	Distance	2341	499.15
Distance	968	515.99	Distance	1819	559.69	Distance	2342	499.36
Distance	861	458.95	Distance	1726	531.08	Distance	2406	513.01
Distance	918	489.34	Distance	1305	401.54	Distance	2310	492.54
Distance	937	499.47	Distance	1345	413.85	Distance	2506	534.33
Distance	972	518.12	Distance	2810	864.62	Distance	2433	518.76
Distance	863	460.02	Distance	2029	624.31	Distance	2374	506.18
Distance	1464	780.38	Distance	2489	765.85	Distance	2348	500.64
Distance	1127	600.75	Distance	2122	652.92	Distance	2242	478.04
Distance	1175	626.33	Distance	2140	658.46	Distance	3098	660.55
Distance	1365	727.61	Distance	2170	667.69			
Distance	1330	708.96	Distance	1145	352.31			
Distance	1355	722.28	Distance	1720	529.23			
Distance	1376	733.48	Distance	1745	536.92			
Distance	1317	702.03	Distance	1951	600.31			
Distance	1231	656.18	Distance	3257	694.46			
Distance	1301	693.50	Distance	2405	740.00			
Distance	1228	654.58	Distance	2440	750.77			
Distance	1151	613.54	Distance	2918	897.85			
Distance	891	474.95	Distance	2394	736.62			
Distance	1250	666.31	Distance	2350	723.08			
Distance	1026	546.91	Distance	2426	746.46			
Distance	1000	533.05	Distance	2435	749.23			
Distance	1529	815.03	Distance	2733	840.92			
Distance	1122	598.08	Distance	2260	695.38			
Distance	1021	544.24	Distance	2308	710.15			
Distance	1603	854.48	Distance	2349	722.77			
Distance	865	461.09	Distance	2674	822.77			
Distance	1206	642.86	Distance	2364	727.38			
Distance	1091	581.56	Distance	3332	1025.23			
Distance	1223	651.92	Distance	2347	722.15			
Distance	1414	753.73	Distance	2258	694.77			
Distance	1214	647.12	Distance	2367	504.69			
Distance	1885	1004.80	Distance	2311	492.75			
Distance	2147	1144.46	Distance	2836	604.69			
Distance	1185	631.66	Distance	2491	531.13			

Appendix D. Substrate 3 Data

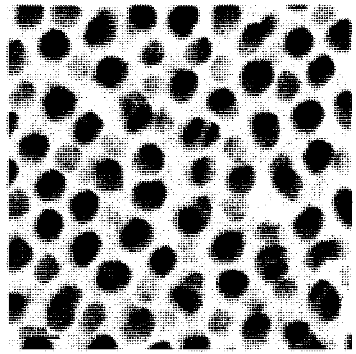
SEM Images for Substrate 3



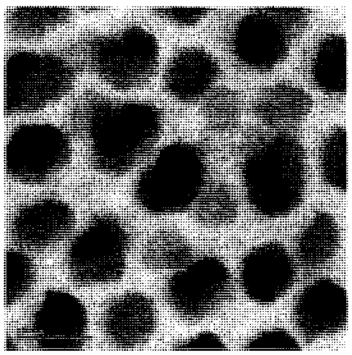
20 K
500 nm = 938 μm



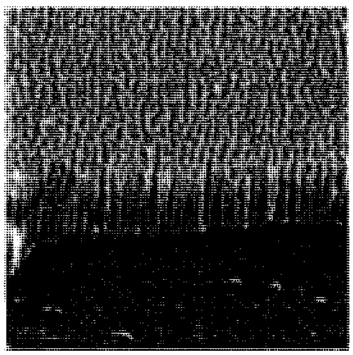
30 K
500 nm = 1425 μm



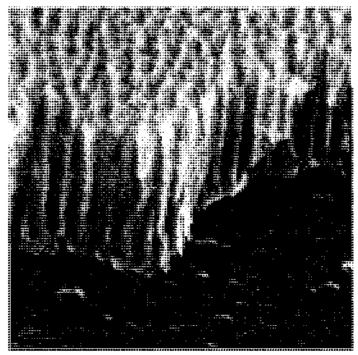
80 K
100 nm = 750 μm



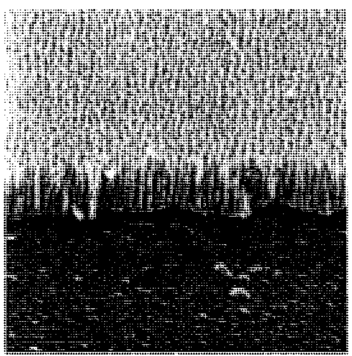
150 K
100 nm = 1425 μm



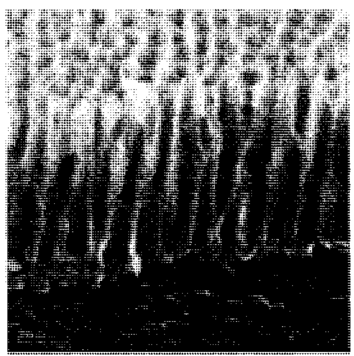
25 K
500 nm = 1188 μm



40 K
200 nm = 750 μm



15 K
1 μm = 1425 μm



50 K
200 nm = 938 μm

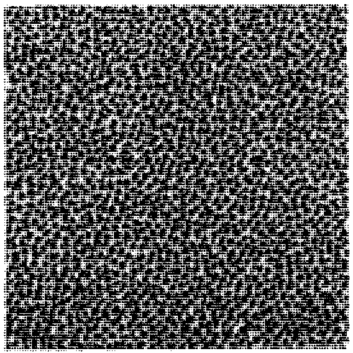
Diameter Measurements for Substrate 3								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	183	97.55	Diameter	151	80.49	Diameter	250	87.72
Diameter	167	89.02	Diameter	158	84.22	Diameter	243	85.26
Diameter	150	79.96	Diameter	149	79.42	Diameter	254	89.12
Diameter	170	90.62	Diameter	153	81.56	Diameter	226	79.30
Diameter	151	80.49	Diameter	159	84.75	Diameter	218	76.49
Diameter	151	80.49	Diameter	142	75.69	Diameter	223	78.25
Diameter	128	68.23	Diameter	158	84.22	Diameter	221	77.54
Diameter	142	75.69	Diameter	186	99.15	Diameter	210	73.68
Diameter	140	74.63	Diameter	194	103.41	Diameter	212	74.39
Diameter	129	68.76	Diameter	165	87.95	Diameter	218	76.49
Diameter	151	80.49	Diameter	163	86.89	Diameter	227	79.65
Diameter	140	74.63	Diameter	182	97.01	Diameter	232	81.40
Diameter	140	74.63	Diameter	154	82.09	Diameter	233	81.75
Diameter	158	84.22	Diameter	163	86.89	Diameter	221	77.54
Diameter	151	80.49	Diameter	143	76.23	Diameter	230	80.70
Diameter	137	73.03	Diameter	146	77.83	Diameter	241	84.56
Diameter	144	76.76	Diameter	180	95.95	Diameter	223	78.25
Diameter	166	88.49	Diameter	177	94.35	Diameter	218	76.49
Diameter	173	92.22	Diameter	156	83.16	Diameter	219	76.84
Diameter	136	72.49	Diameter	167	89.02	Diameter	223	78.25
Diameter	164	87.42	Diameter	166	88.49	Diameter	202	70.88
Diameter	155	82.62	Diameter	177	94.35	Diameter	229	80.35
Diameter	149	79.42	Diameter	150	79.96	Diameter	269	94.39
Diameter	152	81.02	Diameter	248	87.02	Diameter	228	80.00
Diameter	153	81.56	Diameter	212	74.39	Diameter	248	87.02
Diameter	160	85.29	Diameter	181	63.51	Diameter	259	90.88
Diameter	120	63.97	Diameter	242	84.91	Diameter	236	82.81
Diameter	155	82.62	Diameter	237	83.16	Diameter	186	65.26
Diameter	119	63.43	Diameter	238	83.51	Diameter	231	81.05
Diameter	156	83.16	Diameter	217	76.14	Diameter	192	67.37
Diameter	157	83.69	Diameter	216	75.79	Diameter	220	77.19
Diameter	121	64.50	Diameter	204	71.58	Diameter	238	83.51
Diameter	141	75.16	Diameter	234	82.11	Diameter	280	98.25
Diameter	147	78.36	Diameter	197	69.12	Diameter	251	88.07
Diameter	143	76.23	Diameter	207	72.63	Diameter	255	89.47
Diameter	155	82.62	Diameter	175	61.40	Diameter	234	82.11
Diameter	127	67.70	Diameter	240	84.21	Diameter	237	83.16
Diameter	152	81.02	Diameter	214	75.09	Diameter	229	80.35
Diameter	139	74.09	Diameter	206	72.28	Diameter	251	88.07
Diameter	143	76.23	Diameter	215	75.44	Diameter	252	88.42
Diameter	150	79.96	Diameter	250	87.72	Diameter	241	84.56
Diameter	141	75.16	Diameter	225	78.95	Diameter	246	86.32

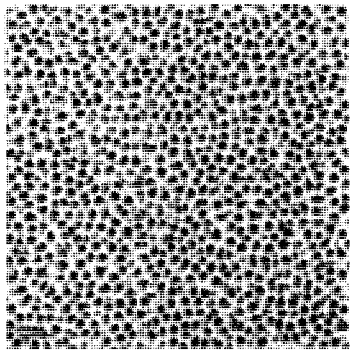
Diameter Measurements for Substrate 3								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	280	98.25	Diameter	503	67.07	Diameter	948	66.53
Diameter	230	80.70	Diameter	555	74.00	Diameter	879	61.68
Diameter	228	80.00	Diameter	615	82.00			
Diameter	261	91.58	Diameter	521	69.47			
Diameter	590	78.67	Diameter	489	65.20			
Diameter	468	62.40	Diameter	598	79.73			
Diameter	374	49.87	Diameter	502	66.93			
Diameter	542	72.27	Diameter	555	74.00			
Diameter	504	67.20	Diameter	521	69.47			
Diameter	601	80.13	Diameter	545	72.67			
Diameter	416	55.47	Diameter	589	78.53			
Diameter	574	76.53	Diameter	439	58.53			
Diameter	572	76.27	Diameter	523	69.73			
Diameter	499	66.53	Diameter	593	79.07			
Diameter	457	60.93	Diameter	614	81.87			
Diameter	579	77.20	Diameter	565	75.33			
Diameter	565	75.33	Diameter	615	82.00			
Diameter	677	90.27	Diameter	564	75.20			
Diameter	610	81.33	Diameter	527	70.27			
Diameter	528	70.40	Diameter	510	68.00			
Diameter	518	69.07	Diameter	585	78.00			
Diameter	505	67.33	Diameter	477	63.60			
Diameter	444	59.20	Diameter	427	56.93			
Diameter	627	83.60	Diameter	523	69.73			
Diameter	560	74.67	Diameter	1023	71.79			
Diameter	590	78.67	Diameter	1023	71.79			
Diameter	498	66.40	Diameter	961	67.44			
Diameter	553	73.73	Diameter	1034	72.56			
Diameter	521	69.47	Diameter	1039	72.91			
Diameter	532	70.93	Diameter	933	65.47			
Diameter	597	79.60	Diameter	815	57.19			
Diameter	554	73.87	Diameter	937	65.75			
Diameter	544	72.53	Diameter	593	41.61			
Diameter	495	66.00	Diameter	1161	81.47			
Diameter	552	73.60	Diameter	1163	81.61			
Diameter	597	79.60	Diameter	1096	76.91			
Diameter	547	72.93	Diameter	641	44.98			
Diameter	551	73.47	Diameter	1082	75.93			
Diameter	553	73.73	Diameter	1018	71.44			
Diameter	584	77.87	Diameter	977	68.56			
Diameter	558	74.40	Diameter	916	64.28			
Diameter	528	70.40	Diameter	857	60.14			

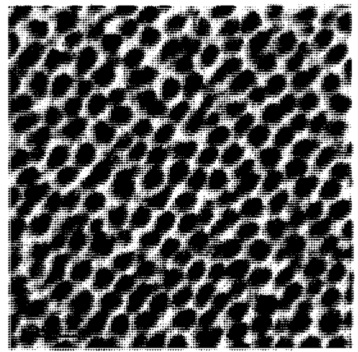
Nanopore Length Measurements for Substrate 3								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1403	590.49	Distance	1838	490.13	Distance	840.00	589.47
Distance	1360	572.39	Distance	2117	564.53	Distance	812.00	569.82
Distance	1326	558.08	Distance	2015	537.33	Distance	3150	671.64
Distance	1448	609.43	Distance	1475	393.33	Distance	3177	677.40
Distance	1556	654.88	Distance	2402	640.53	Distance	3084	657.57
Distance	1470	618.69	Distance	2228	594.13	Distance	3109	662.90
Distance	1601	673.82	Distance	1013	710.88	Distance	3104	661.83
Distance	1574	662.46	Distance	938	658.25	Distance	2929	624.52
Distance	1524	641.41	Distance	938	658.25	Distance	2890	616.20
Distance	1527	642.68	Distance	854	599.30	Distance	3026	645.20
Distance	1459	614.06	Distance	915	642.11	Distance	2906	619.62
Distance	1478	622.05	Distance	876	614.74	Distance	2450	522.39
Distance	1393	586.28	Distance	866	607.72	Distance	2698	575.27
Distance	1417	596.38	Distance	791	555.09	Distance	2833	604.05
Distance	1472	619.53	Distance	740	519.30	Distance	2569	547.76
Distance	1558	655.72	Distance	768	538.95			
Distance	1397	587.96	Distance	740	519.30			
Distance	1244	523.57	Distance	728	510.88			
Distance	1414	595.12	Distance	964	676.49			
Distance	1478	622.05	Distance	867	608.42			
Distance	1243	523.15	Distance	845	592.98			
Distance	1355	570.29	Distance	895	628.07			
Distance	1355	570.29	Distance	843	591.58			
Distance	1414	595.12	Distance	790	554.39			
Distance	1373	577.86	Distance	826	579.65			
Distance	1425	599.75	Distance	794	557.19			
Distance	2013	536.80	Distance	820	575.44			
Distance	2079	554.40	Distance	904	634.39			
Distance	2016	537.60	Distance	906	635.79			
Distance	2018	538.13	Distance	868	609.12			
Distance	2232	595.20	Distance	763	535.44			
Distance	2213	590.13	Distance	750	526.32			
Distance	2118	564.80	Distance	781	548.07			
Distance	2179	581.07	Distance	898	630.18			
Distance	2115	564.00	Distance	830	582.46			
Distance	2314	617.07	Distance	802	562.81			
Distance	2325	620.00	Distance	795	557.89			
Distance	2269	605.07	Distance	827	580.35			
Distance	2206	588.27	Distance	805	564.91			
Distance	2005	534.67	Distance	811	569.12			
Distance	2021	538.93	Distance	827	580.35			
Distance	2050	546.67	Distance	863	605.61			

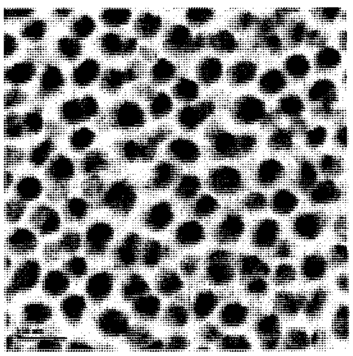
Appendix E. Substrate 4 Data

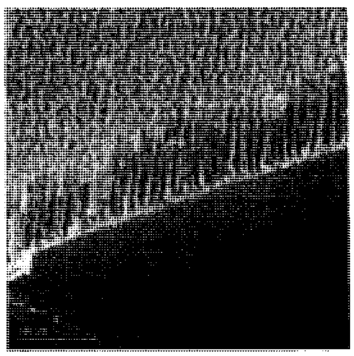
SEM Images for Substrate 4

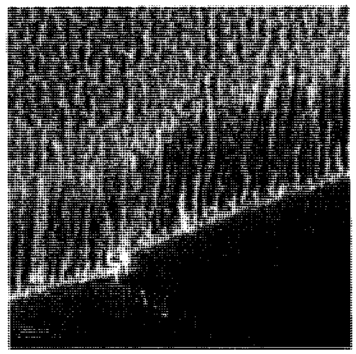

25 K
500 nm =1188 μm

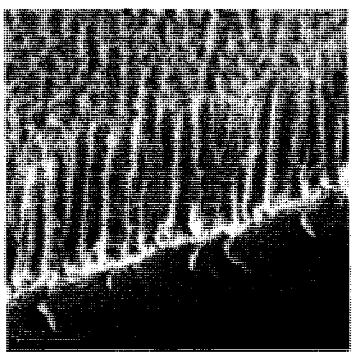

30 K
500 nm = 1425 μm

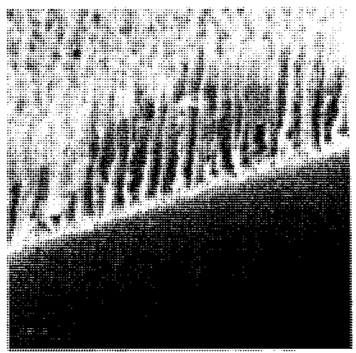

70 K
200 nm = 1325 μm


100 K
100 nm = 938 μm


30 K
500 nm = 1425 μm


40 K
200 nm = 750 μm


60 K
200 nm = 1138 μm


50 K
200 nm = 938 μm

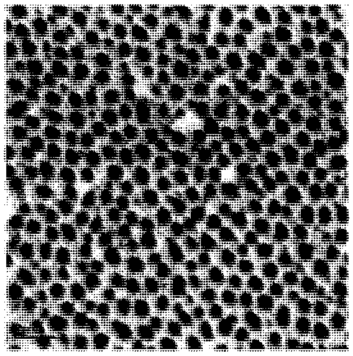
Diameter Measurements for Substrate 4								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	127	44.56	Diameter	144	50.53	Diameter	260	55.44
Diameter	91	31.93	Diameter	149	52.28	Diameter	219	46.70
Diameter	141	49.47	Diameter	114	40.00	Diameter	197	42.00
Diameter	100	35.09	Diameter	187	65.61	Diameter	266	56.72
Diameter	186	65.26	Diameter	146	51.23	Diameter	168	35.82
Diameter	174	61.05	Diameter	103	36.14	Diameter	159	33.90
Diameter	165	57.89	Diameter	132	46.32	Diameter	170	36.25
Diameter	98	34.39	Diameter	140	49.12	Diameter	223	47.55
Diameter	146	51.23	Diameter	165	57.89	Diameter	264	56.29
Diameter	124	43.51	Diameter	122	42.81	Diameter	269	57.36
Diameter	144	50.53	Diameter	161	56.49	Diameter	253	53.94
Diameter	126	44.21	Diameter	176	61.75	Diameter	221	47.12
Diameter	155	54.39	Diameter	189	66.32	Diameter	332	70.79
Diameter	119	41.75	Diameter	168	58.95	Diameter	290	61.83
Diameter	147	51.58	Diameter	171	60.00	Diameter	212	45.20
Diameter	146	51.23	Diameter	171	60.00	Diameter	323	68.87
Diameter	123	43.16	Diameter	190	66.67	Diameter	179	38.17
Diameter	148	51.93	Diameter	172	60.35	Diameter	303	64.61
Diameter	154	54.04	Diameter	135	47.37	Diameter	234	49.89
Diameter	116	40.70	Diameter	135	47.37	Diameter	246	52.45
Diameter	117	41.05	Diameter	172	60.35	Diameter	282	60.13
Diameter	143	50.18	Diameter	168	58.95	Diameter	243	51.81
Diameter	166	58.25	Diameter	172	60.35	Diameter	210	44.78
Diameter	160	56.14	Diameter	327	69.72	Diameter	180	38.38
Diameter	131	45.96	Diameter	175	37.31	Diameter	224	47.76
Diameter	119	41.75	Diameter	195	41.58	Diameter	402	85.71
Diameter	126	44.21	Diameter	204	43.50	Diameter	385	82.09
Diameter	127	44.56	Diameter	242	51.60	Diameter	204	43.50
Diameter	147	51.58	Diameter	245	52.24	Diameter	192	40.94
Diameter	129	45.26	Diameter	251	53.52	Diameter	254	54.16
Diameter	136	47.72	Diameter	213	45.42	Diameter	207	44.14
Diameter	185	64.91	Diameter	177	37.74	Diameter	172	36.67
Diameter	83	29.12	Diameter	193	41.15	Diameter	241	51.39
Diameter	126	44.21	Diameter	228	48.61	Diameter	269	57.36
Diameter	153	53.68	Diameter	293	62.47	Diameter	243	51.81
Diameter	171	60.00	Diameter	253	53.94	Diameter	232	49.47
Diameter	111	38.95	Diameter	260	55.44	Diameter	282	60.13
Diameter	149	52.28	Diameter	219	46.70	Diameter	304	64.82
Diameter	161	56.49	Diameter	271	57.78	Diameter	304	64.82
Diameter	145	50.88	Diameter	218	46.48	Diameter	232	49.47
Diameter	164	57.54	Diameter	231	49.25	Diameter	148	31.56
Diameter	151	52.98	Diameter	280	59.70	Diameter	163	34.75

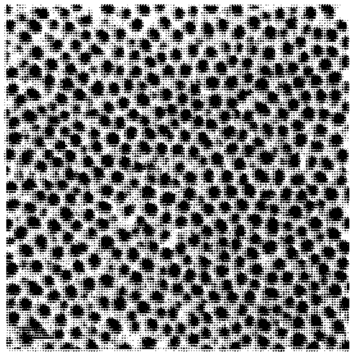
Diameter Measurements for Substrate 4								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	261	55.65	Diameter	271	57.78	Diameter	383	57.81
Diameter	285	60.77	Diameter	212	45.20	Diameter	217	32.75
Diameter	238	50.75	Diameter	204	43.50	Diameter	295	44.53
Diameter	235	50.11	Diameter	241	51.39	Diameter	343	51.77
Diameter	176	37.53	Diameter	240	51.17	Diameter	305	46.04
Diameter	203	43.28	Diameter	190	40.51	Diameter	301	45.43
Diameter	226	48.19	Diameter	259	55.22	Diameter	367	55.40
Diameter	181	38.59	Diameter	218	46.48	Diameter	317	47.85
Diameter	187	39.87	Diameter	225	47.97	Diameter	301	45.43
Diameter	191	40.72	Diameter	185	39.45	Diameter	391	59.02
Diameter	145	30.92	Diameter	221	47.12	Diameter	194	29.28
Diameter	158	33.69	Diameter	194	41.36	Diameter	243	36.68
Diameter	190	40.51	Diameter	217	46.27	Diameter	368	55.55
Diameter	205	43.71	Diameter	175	37.31	Diameter	245	36.98
Diameter	237	50.53	Diameter	229	48.83	Diameter	330	49.81
Diameter	208	44.35	Diameter	212	45.20	Diameter	262	39.55
Diameter	222	47.33	Diameter	259	55.22	Diameter	295	44.53
Diameter	254	54.16	Diameter	210	44.78	Diameter	266	40.15
Diameter	212	45.20	Diameter	192	40.94	Diameter	286	43.17
Diameter	207	44.14	Diameter	200	42.64	Diameter	267	40.30
Diameter	207	44.14	Diameter	217	46.27	Diameter	293	44.23
Diameter	192	40.94	Diameter	182	38.81	Diameter	312	47.09
Diameter	198	42.22	Diameter	182	38.81	Diameter	438	66.11
Diameter	252	53.73	Diameter	212	45.20	Diameter	280	42.26
Diameter	179	38.17	Diameter	214	45.63	Diameter	394	59.47
Diameter	271	57.78	Diameter	207	44.14	Diameter	465	70.19
Diameter	174	37.10	Diameter	215	45.84	Diameter	426	64.30
Diameter	233	49.68	Diameter	390	58.87	Diameter	338	51.02
Diameter	185	39.45	Diameter	404	60.98	Diameter	277	41.81
Diameter	189	40.30	Diameter	356	53.74	Diameter	436	65.81
Diameter	197	42.00	Diameter	380	57.36	Diameter	265	40.00
Diameter	205	43.71	Diameter	261	39.40	Diameter	451	68.08
Diameter	257	54.80	Diameter	421	63.55	Diameter	290	43.77
Diameter	225	47.97	Diameter	421	63.55	Diameter	319	48.15
Diameter	199	42.43	Diameter	365	55.09	Diameter	326	49.21
Diameter	203	43.28	Diameter	358	54.04	Diameter	298	44.98
Diameter	215	45.84	Diameter	369	55.70	Diameter	228	34.42
Diameter	243	51.81	Diameter	235	35.47	Diameter	360	54.34
Diameter	188	40.09	Diameter	269	40.60	Diameter	338	51.02
Diameter	312	66.52	Diameter	498	75.17	Diameter	408	61.58
Diameter	229	48.83	Diameter	336	50.72	Diameter	285	43.02
Diameter	184	39.23	Diameter	354	53.43	Diameter	368	55.55

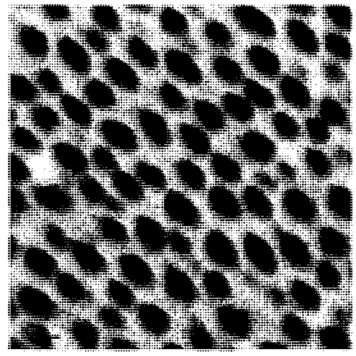
Nanopore Length Measurements for Substrate 4								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1315	553.45	Distance	1967	524.53	Distance	2322	495.10
Distance	1389	584.60	Distance	1873	499.47	Distance	2613	557.14
Distance	1439	605.64	Distance	1984	529.07	Distance	2382	507.89
Distance	1300	547.14	Distance	1926	513.60	Distance	2385	508.53
Distance	1250	526.09	Distance	1953	520.80	Distance	2350	501.07
Distance	1251	526.52	Distance	1931	514.93	Distance	2452	522.81
Distance	1201	505.47	Distance	2028	540.80	Distance	2409	513.65
Distance	1263	531.57	Distance	1851	493.60	Distance	2492	531.34
Distance	1325	557.66	Distance	1934	515.73	Distance	2403	512.37
Distance	1313	552.61	Distance	1974	526.40	Distance	2388	509.17
Distance	1278	537.88	Distance	1902	507.20	Distance	2412	514.29
Distance	1302	547.98	Distance	1877	500.53	Distance	2404	512.58
Distance	1216	511.78	Distance	1968	524.80	Distance	2757	587.85
Distance	1401	589.65	Distance	1960	522.67	Distance	2320	494.67
Distance	1414	595.12	Distance	1990	530.67	Distance	2430	518.12
Distance	1523	640.99	Distance	1956	521.60	Distance	1869	498.40
Distance	1570	660.77	Distance	1993	531.47	Distance	2546	542.86
Distance	1642	691.08	Distance	2453	523.03			
Distance	1375	578.70	Distance	2428	517.70			
Distance	1406	591.75	Distance	2671	569.51			
Distance	1346	566.50	Distance	2413	514.50			
Distance	1406	591.75	Distance	2372	505.76			
Distance	1391	585.44	Distance	2447	521.75			
Distance	1382	581.65	Distance	2421	516.20			
Distance	1268	533.67	Distance	2278	485.71			
Distance	1374	578.28	Distance	2338	498.51			
Distance	1398	588.38	Distance	2327	496.16			
Distance	1295	545.03	Distance	2442	520.68			
Distance	1332	560.61	Distance	2412	514.29			
Distance	1307	550.08	Distance	2493	531.56			
Distance	1200	505.05	Distance	2546	542.86			
Distance	1217	512.21	Distance	2363	503.84			
Distance	1288	542.09	Distance	2486	530.06			
Distance	2076	553.60	Distance	2117	451.39			
Distance	2039	543.73	Distance	2507	534.54			
Distance	1975	526.67	Distance	2368	504.90			
Distance	1940	517.33	Distance	3332	710.45			
Distance	1936	516.27	Distance	2448	521.96			
Distance	1901	506.93	Distance	2420	515.99			
Distance	1893	504.80	Distance	2496	532.20			
Distance	2046	545.60	Distance	2368	504.90			

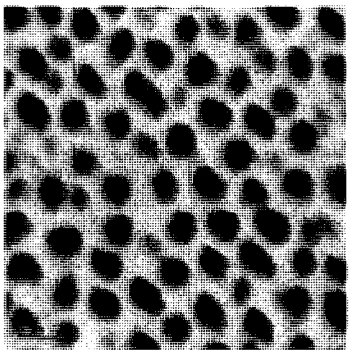
Appendix F. Substrate 5 Data

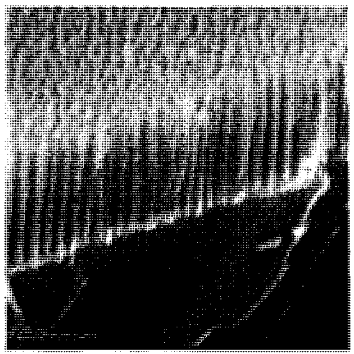
SEM Images for Substrate 5

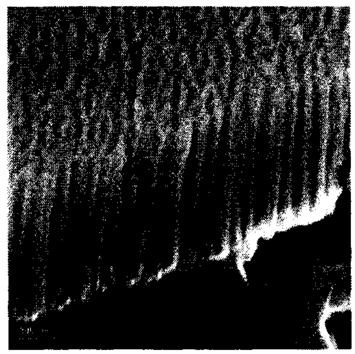

40 K
200 nm = 750 μm

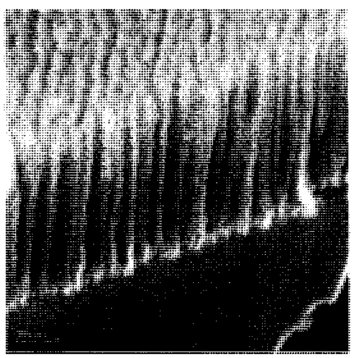

35 K
200 nm = 650 μm

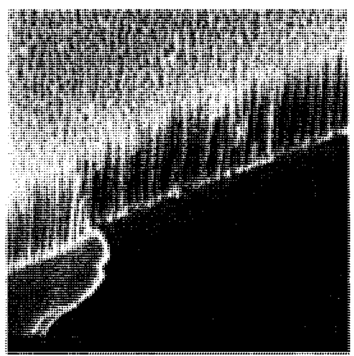

80 K
100 nm = 750 μm


90 K
100 nm = 850 μm


30 K
500 nm = 1425 μm


35 K
200 nm = 650 μm


40 K
200 nm = 750 μm


20 K
500 nm = 1425 μm

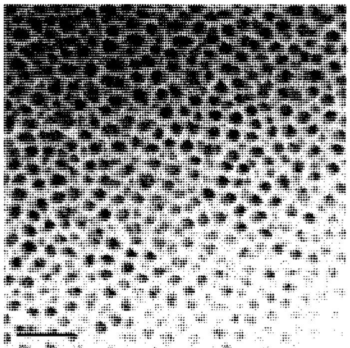
Diameter Measurements for Substrate 5								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	272	72.53	Diameter	221	58.93	Diameter	211	64.92
Diameter	264	70.40	Diameter	229	61.07	Diameter	184	56.62
Diameter	267	71.20	Diameter	278	74.13	Diameter	209	64.31
Diameter	232	61.87	Diameter	298	79.47	Diameter	244	75.08
Diameter	268	71.47	Diameter	245	65.33	Diameter	232	71.38
Diameter	305	81.33	Diameter	272	72.53	Diameter	214	65.85
Diameter	290	77.33	Diameter	270	72.00	Diameter	257	79.08
Diameter	280	74.67	Diameter	262	69.87	Diameter	224	68.92
Diameter	243	64.80	Diameter	296	78.93	Diameter	213	65.54
Diameter	235	62.67	Diameter	269	71.73	Diameter	227	69.85
Diameter	285	76.00	Diameter	289	77.07	Diameter	195	60.00
Diameter	226	60.27	Diameter	302	80.53	Diameter	212	65.23
Diameter	268	71.47	Diameter	264	70.40	Diameter	238	73.23
Diameter	289	77.07	Diameter	247	65.87	Diameter	228	70.15
Diameter	270	72.00	Diameter	241	64.27	Diameter	262	80.62
Diameter	256	68.27	Diameter	257	68.53	Diameter	217	66.77
Diameter	274	73.07	Diameter	258	68.80	Diameter	204	62.77
Diameter	236	62.93	Diameter	274	73.07	Diameter	236	72.62
Diameter	272	72.53	Diameter	302	80.53	Diameter	222	68.31
Diameter	223	59.47	Diameter	314	83.73	Diameter	210	64.62
Diameter	259	69.07	Diameter	310	82.67	Diameter	271	83.38
Diameter	276	73.60	Diameter	278	74.13	Diameter	211	64.92
Diameter	333	88.80	Diameter	276	73.60	Diameter	238	73.23
Diameter	233	62.13	Diameter	227	69.85	Diameter	190	58.46
Diameter	289	77.07	Diameter	166	51.08	Diameter	220	67.69
Diameter	241	64.27	Diameter	263	80.92	Diameter	214	65.85
Diameter	236	62.93	Diameter	200	61.54	Diameter	227	69.85
Diameter	263	70.13	Diameter	161	49.54	Diameter	244	75.08
Diameter	233	62.13	Diameter	183	56.31	Diameter	242	74.46
Diameter	273	72.80	Diameter	211	64.92	Diameter	249	76.62
Diameter	208	55.47	Diameter	189	58.15	Diameter	237	72.92
Diameter	236	62.93	Diameter	206	63.38	Diameter	209	64.31
Diameter	294	78.40	Diameter	224	68.92	Diameter	228	70.15
Diameter	266	70.93	Diameter	166	51.08	Diameter	244	75.08
Diameter	279	74.40	Diameter	207	63.69	Diameter	231	71.08
Diameter	322	85.87	Diameter	207	63.69	Diameter	240	73.85
Diameter	303	80.80	Diameter	188	57.85	Diameter	216	66.46
Diameter	283	75.47	Diameter	209	64.31	Diameter	241	74.15
Diameter	300	80.00	Diameter	237	72.92	Diameter	248	76.31
Diameter	309	82.40	Diameter	215	66.15	Diameter	242	74.46
Diameter	248	66.13	Diameter	192	59.08	Diameter	198	60.92

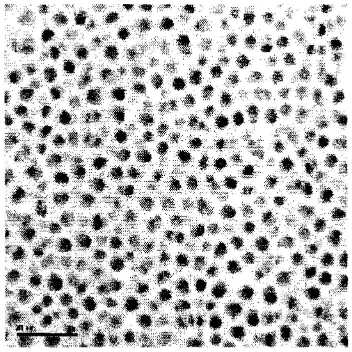
Diameter Measurements for Substrate 5								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	230	70.77	Diameter	371	49.47	Diameter	436	51.29
Diameter	242	74.46	Diameter	366	48.80	Diameter	584	68.71
Diameter	235	72.31	Diameter	437	58.27	Diameter	507	59.65
Diameter	238	73.23	Diameter	388	51.73	Diameter	506	59.53
Diameter	509	67.87	Diameter	534	71.20	Diameter	478	56.24
Diameter	459	61.20	Diameter	384	51.20	Diameter	610	71.76
Diameter	522	69.60	Diameter	428	57.07	Diameter	546	64.24
Diameter	401	53.47	Diameter	387	51.60	Diameter	353	41.53
Diameter	522	69.60	Diameter	424	56.53	Diameter	700	82.35
Diameter	424	56.53	Diameter	417	55.60	Diameter	565	66.47
Diameter	526	70.13	Diameter	442	58.93	Diameter	580	68.24
Diameter	310	41.33	Diameter	434	57.87	Diameter	577	67.88
Diameter	423	56.40	Diameter	467	62.27	Diameter	516	60.71
Diameter	430	57.33	Diameter	424	56.53	Diameter	517	60.82
Diameter	438	58.40	Diameter	462	61.60	Diameter	483	56.82
Diameter	508	67.73	Diameter	458	61.07	Diameter	505	59.41
Diameter	374	49.87	Diameter	499	66.53	Diameter	445	52.35
Diameter	442	58.93	Diameter	422	56.27	Diameter	493	58.00
Diameter	458	61.07	Diameter	365	48.67	Diameter	254	29.88
Diameter	469	62.53	Diameter	498	66.40	Diameter	549	64.59
Diameter	495	66.00	Diameter	472	62.93	Diameter	307	36.12
Diameter	501	66.80	Diameter	418	55.73	Diameter	515	60.59
Diameter	334	44.53	Diameter	391	52.13	Diameter	592	69.65
Diameter	468	62.40	Diameter	460	61.33	Diameter	592	69.65
Diameter	470	62.67	Diameter	451	60.13	Diameter	268	31.53
Diameter	498	66.40	Diameter	458	61.07	Diameter	389	45.76
Diameter	336	44.80	Diameter	453	60.40	Diameter	385	45.29
Diameter	521	69.47	Diameter	721	84.82	Diameter	451	53.06
Diameter	377	50.27	Diameter	463	54.47	Diameter	487	57.29
Diameter	548	73.07	Diameter	502	59.06	Diameter	578	68.00
Diameter	514	68.53	Diameter	514	60.47	Diameter	463	54.47
Diameter	440	58.67	Diameter	479	56.35	Diameter	452	53.18
Diameter	492	65.60	Diameter	574	67.53	Diameter	561	66.00
Diameter	488	65.07	Diameter	404	47.53	Diameter	519	61.06
Diameter	371	49.47	Diameter	440	51.76	Diameter	462	54.35
Diameter	338	45.07	Diameter	497	58.47	Diameter	337	39.65
Diameter	463	61.73	Diameter	287	33.76	Diameter	409	48.12
Diameter	414	55.20	Diameter	550	64.71	Diameter	518	60.94
Diameter	366	48.80	Diameter	507	59.65	Diameter	452	53.18
Diameter	242	32.27	Diameter	399	46.94	Diameter	530	62.35
Diameter	441	58.80	Diameter	549	64.59	Diameter	417	49.06

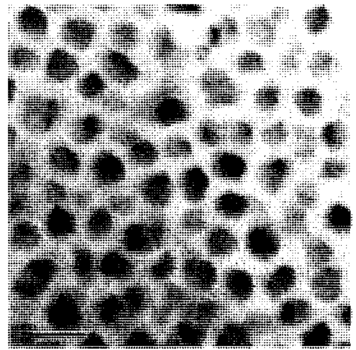
Nanopore Length Measurements for Substrate 5								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	2049	718.95	Distance	2537	780.62	Distance	1367	690.40
Distance	2078	729.12	Distance	2422	745.23	Distance	1356	684.85
Distance	2035	714.04	Distance	2903	774.13	Distance	1326	669.70
Distance	2075	728.07	Distance	2761	736.27	Distance	1272	642.42
Distance	2140	750.88	Distance	2877	767.20	Distance	1227	619.70
Distance	2040	715.79	Distance	2466	657.60	Distance	1227	619.70
Distance	1957	686.67	Distance	2775	740.00	Distance	1190	601.01
Distance	1956	686.32	Distance	2853	760.80	Distance	1288	650.51
Distance	2044	717.19	Distance	2603	694.13	Distance	1357	685.35
Distance	2032	712.98	Distance	2673	712.80	Distance	1357	685.35
Distance	1960	687.72	Distance	2633	702.13	Distance	1365	689.39
Distance	1797	630.53	Distance	2585	689.33	Distance	1392	703.03
Distance	1850	649.12	Distance	2677	713.87	Distance	1504	759.60
Distance	2066	724.91	Distance	2629	701.07	Distance	1430	722.22
Distance	1914	671.58	Distance	2751	733.60	Distance	1338	675.76
Distance	1865	654.39	Distance	2702	720.53	Distance	1394	704.04
Distance	1901	667.02	Distance	2689	717.07	Distance	1351	682.32
Distance	2039	715.44	Distance	2712	723.20	Distance	1289	651.01
Distance	2015	707.02	Distance	2802	747.20	Distance	1376	694.95
Distance	2030	712.28	Distance	2444	651.73	Distance	1338	675.76
Distance	2121	744.21	Distance	2306	614.93	Distance	1423	718.69
Distance	2118	743.16	Distance	2760	736.00	Distance	2528	777.85
Distance	2145	752.63	Distance	1493	754.04			
Distance	2021	709.12	Distance	1425	719.70			
Distance	2310	710.77	Distance	1369	691.41			
Distance	2275	700.00	Distance	1396	705.05			
Distance	2277	700.62	Distance	1331	672.22			
Distance	2177	669.85	Distance	1419	716.67			
Distance	2280	701.54	Distance	1341	677.27			
Distance	2482	763.69	Distance	1417	715.66			
Distance	2666	820.31	Distance	1385	699.49			
Distance	2530	778.46	Distance	1469	741.92			
Distance	2475	761.54	Distance	1474	744.44			
Distance	2525	776.92	Distance	1409	711.62			
Distance	2615	804.62	Distance	1316	664.65			
Distance	2556	786.46	Distance	1310	661.62			
Distance	2492	766.77	Distance	1270	641.41			
Distance	2510	772.31	Distance	1428	721.21			
Distance	2407	740.62	Distance	1340	676.77			
Distance	2509	772.00	Distance	1403	708.59			
Distance	2480	763.08	Distance	1403	708.59			

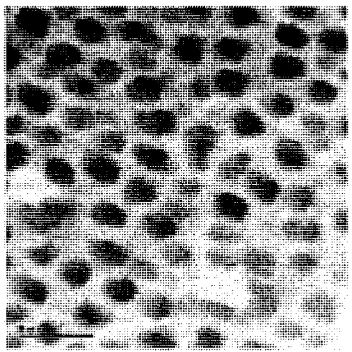
Appendix G. Substrate 6 Data

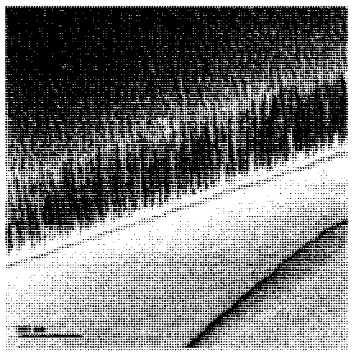
SEM Images for Substrate 6

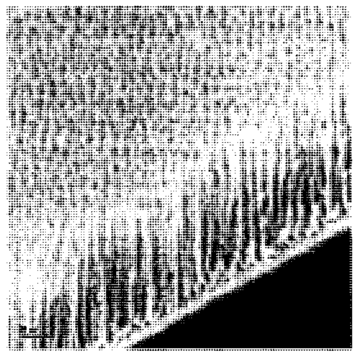

60 K
200 nm = 138 μm

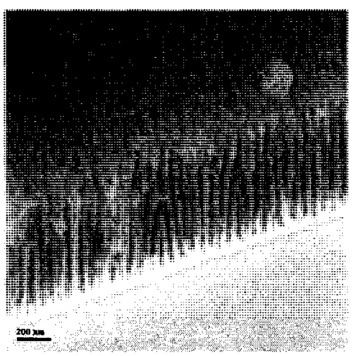

60 K
200 nm = 1138 μm

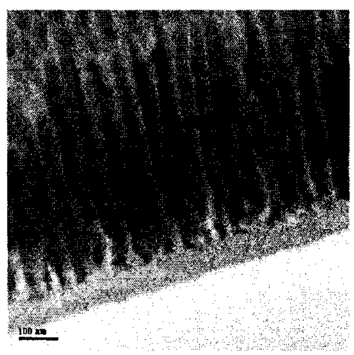

130 K
100 nm = 1125 μm


130 K
100 nm = 1125 μm


25 K
500 nm = 1188 μm


35 K
200 nm = 650 μm


35 K
200 nm = 650 μm


80 K
100 nm = 750 μm

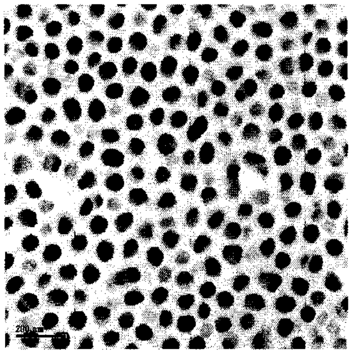
Diameter Measurements for Substrate 6								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	205	36.03	Diameter	196	34.45	Diameter	243	42.71
Diameter	171	30.05	Diameter	194	34.09	Diameter	248	43.59
Diameter	185	32.51	Diameter	231	40.60	Diameter	243	42.71
Diameter	236	41.48	Diameter	266	46.75	Diameter	247	43.41
Diameter	218	38.31	Diameter	267	46.92	Diameter	253	44.46
Diameter	188	33.04	Diameter	194	34.09	Diameter	227	39.89
Diameter	165	29.00	Diameter	250	43.94	Diameter	216	37.96
Diameter	191	33.57	Diameter	222	39.02	Diameter	215	37.79
Diameter	242	42.53	Diameter	210	36.91	Diameter	263	46.22
Diameter	189	33.22	Diameter	222	39.02	Diameter	263	46.22
Diameter	279	49.03	Diameter	236	41.48	Diameter	222	39.02
Diameter	201	35.33	Diameter	211	37.08	Diameter	211	37.08
Diameter	190	33.39	Diameter	236	41.48	Diameter	160	28.12
Diameter	199	34.97	Diameter	257	45.17	Diameter	260	45.69
Diameter	212	37.26	Diameter	243	42.71	Diameter	212	37.26
Diameter	221	38.84	Diameter	237	41.65	Diameter	222	39.02
Diameter	198	34.80	Diameter	237	41.65	Diameter	257	45.17
Diameter	206	36.20	Diameter	234	41.12	Diameter	213	37.43
Diameter	204	35.85	Diameter	231	40.60	Diameter	304	53.43
Diameter	182	31.99	Diameter	195	34.27	Diameter	225	39.54
Diameter	192	33.74	Diameter	198	34.80	Diameter	255	44.82
Diameter	209	36.73	Diameter	236	41.48	Diameter	242	42.53
Diameter	224	39.37	Diameter	229	40.25	Diameter	256	44.99
Diameter	185	32.51	Diameter	173	30.40	Diameter	276	48.51
Diameter	226	39.72	Diameter	236	41.48	Diameter	241	42.36
Diameter	226	39.72	Diameter	228	40.07	Diameter	231	40.60
Diameter	181	31.81	Diameter	207	36.38	Diameter	236	41.48
Diameter	261	45.87	Diameter	171	30.05	Diameter	283	49.74
Diameter	211	37.08	Diameter	246	43.23	Diameter	193	33.92
Diameter	219	38.49	Diameter	208	36.56	Diameter	259	45.52
Diameter	218	38.31	Diameter	227	39.89	Diameter	244	42.88
Diameter	202	35.50	Diameter	263	46.22	Diameter	235	41.30
Diameter	214	37.61	Diameter	235	41.30	Diameter	233	40.95
Diameter	225	39.54	Diameter	180	31.63	Diameter	269	47.28
Diameter	258	45.34	Diameter	191	33.57	Diameter	252	44.29
Diameter	202	35.50	Diameter	254	44.64	Diameter	221	38.84
Diameter	235	41.30	Diameter	260	45.69	Diameter	286	50.26
Diameter	232	40.77	Diameter	259	45.52	Diameter	233	40.95
Diameter	216	37.96	Diameter	213	37.43	Diameter	264	46.40
Diameter	207	36.38	Diameter	156	27.42	Diameter	251	44.11
Diameter	211	37.08	Diameter	188	33.04	Diameter	240	42.18

Diameter Measurements for Substrate 6								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	261	45.87	Diameter	429	38.13	Diameter	365	32.44
Diameter	234	41.12	Diameter	432	38.40	Diameter	396	35.20
Diameter	226	39.72	Diameter	416	36.98	Diameter	442	39.29
Diameter	245	43.06	Diameter	409	36.36	Diameter	527	46.84
Diameter	503	44.71	Diameter	434	38.58	Diameter	517	45.96
Diameter	442	39.29	Diameter	508	45.16	Diameter	406	36.09
Diameter	581	51.64	Diameter	485	43.11	Diameter	455	40.44
Diameter	400	35.56	Diameter	403	35.82	Diameter	451	40.09
Diameter	477	42.40	Diameter	513	45.60	Diameter	452	40.18
Diameter	515	45.78	Diameter	412	36.62	Diameter	337	29.96
Diameter	558	49.60	Diameter	493	43.82	Diameter	389	34.58
Diameter	339	30.13	Diameter	509	45.24	Diameter	523	46.49
Diameter	517	45.96	Diameter	422	37.51	Diameter	440	39.11
Diameter	417	37.07	Diameter	451	40.09	Diameter	427	37.96
Diameter	510	45.33	Diameter	410	36.44	Diameter	531	47.20
Diameter	488	43.38	Diameter	442	39.29	Diameter	483	42.93
Diameter	341	30.31	Diameter	374	33.24	Diameter	504	44.80
Diameter	244	21.69	Diameter	392	34.84	Diameter	435	38.67
Diameter	415	36.89	Diameter	394	35.02	Diameter	538	47.82
Diameter	379	33.69	Diameter	441	39.20	Diameter	504	44.80
Diameter	358	31.82	Diameter	448	39.82	Diameter	461	40.98
Diameter	422	37.51	Diameter	550	48.89	Diameter	507	45.07
Diameter	476	42.31	Diameter	481	42.76	Diameter	421	37.42
Diameter	516	45.87	Diameter	515	45.78	Diameter	438	38.93
Diameter	472	41.96	Diameter	453	40.27	Diameter	451	40.09
Diameter	419	37.24	Diameter	542	48.18	Diameter	457	40.62
Diameter	459	40.80	Diameter	450	40.00	Diameter	377	33.51
Diameter	525	46.67	Diameter	486	43.20	Diameter	365	32.44
Diameter	449	39.91	Diameter	566	50.31	Diameter	515	45.78
Diameter	493	43.82	Diameter	518	46.04	Diameter	532	47.29
Diameter	538	47.82	Diameter	574	51.02	Diameter	454	40.36
Diameter	445	39.56	Diameter	590	52.44	Diameter	481	42.76
Diameter	368	32.71	Diameter	473	42.04	Diameter	445	39.56
Diameter	370	32.89	Diameter	531	47.20	Diameter	460	40.89
Diameter	431	38.31	Diameter	538	47.82	Diameter	446	39.64
Diameter	461	40.98	Diameter	323	28.71	Diameter	498	44.27
Diameter	456	40.53	Diameter	305	27.11	Diameter	524	46.58
Diameter	491	43.64	Diameter	371	32.98	Diameter	454	40.36
Diameter	428	38.04	Diameter	588	52.27	Diameter	565	50.22
Diameter	419	37.24	Diameter	514	45.69	Diameter	416	36.98
Diameter	367	32.62	Diameter	368	32.71	Diameter	450	40.00

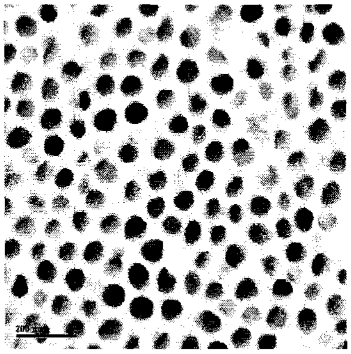
Nanopore Length Measurements for Substrate 6								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1300	547.14	Distance	1942	597.54	Distance	2202	677.54
Distance	1206	507.58	Distance	1851	569.54	Distance	2123	653.23
Distance	1179	496.21	Distance	1838	565.54	Distance	2038	627.08
Distance	1136	478.11	Distance	1788	550.15	Distance	2075	638.46
Distance	1151	484.43	Distance	1802	554.46	Distance	1901	584.92
Distance	1176	494.95	Distance	1737	534.46	Distance	1892	582.15
Distance	1149	483.59	Distance	1915	589.23	Distance	2101	646.46
Distance	1201	505.47	Distance	1838	565.54	Distance	2230	686.15
Distance	1200	505.05	Distance	1815	558.46	Distance	2232	686.77
Distance	1277	537.46	Distance	1841	566.46	Distance	2189	673.54
Distance	1225	515.57	Distance	1702	523.69	Distance	2193	674.77
Distance	1219	513.05	Distance	1758	540.92	Distance	3856	514.13
Distance	1190	500.84	Distance	3412	1049.85	Distance	3919	522.53
Distance	1086	457.07	Distance	1909	587.38	Distance	3891	518.80
Distance	1141	480.22	Distance	1843	567.08	Distance	3920	522.67
Distance	1149	483.59	Distance	1714	527.38	Distance	3989	531.87
Distance	1115	469.28	Distance	1614	496.62	Distance	3820	509.33
Distance	1081	454.97	Distance	1614	496.62	Distance	3929	523.87
Distance	1090	458.75	Distance	1589	488.92	Distance	3781	504.13
Distance	1185	498.74	Distance	1739	535.08	Distance	3770	502.67
Distance	1102	463.80	Distance	1739	535.08	Distance	3836	511.47
Distance	1153	485.27	Distance	1764	542.77	Distance	3775	503.33
Distance	1264	531.99	Distance	1634	502.77	Distance	3697	492.93
Distance	1268	533.67	Distance	2170	667.69	Distance	2216	681.85
Distance	1208	508.42	Distance	1656	509.54	Distance	1763	542.46
Distance	1250	526.09	Distance	1671	514.15			
Distance	1301	547.56	Distance	2191	674.15			
Distance	1076	452.86	Distance	2088	642.46			
Distance	1203	506.31	Distance	2083	640.92			
Distance	1179	496.21	Distance	2022	622.15			
Distance	1213	510.52	Distance	2243	690.15			
Distance	1211	509.68	Distance	2284	702.77			
Distance	1194	502.53	Distance	2246	691.08			
Distance	1062	446.97	Distance	2164	665.85			
Distance	1275	536.62	Distance	1942	597.54			
Distance	1279	538.30	Distance	1829	562.77			
Distance	1243	523.15	Distance	2004	616.62			
Distance	1229	517.26	Distance	2239	688.92			
Distance	1703	716.75	Distance	1855	570.77			
Distance	2000	615.38	Distance	2035	626.15			
Distance	1943	597.85	Distance	2227	685.23			

Appendix H. Substrate 7 Data

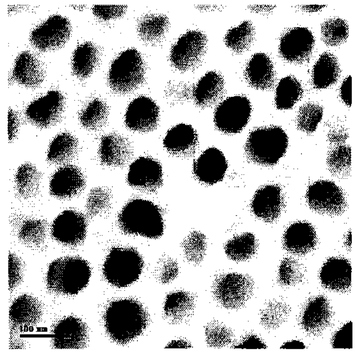
SEM Images for Substrate 7



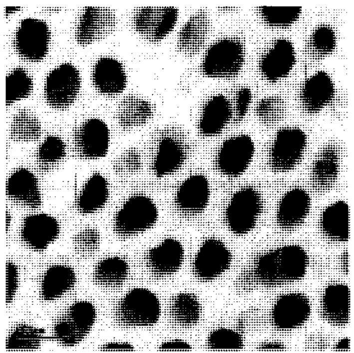
50 K
200 nm = 938 μm



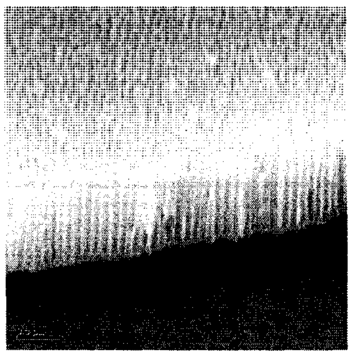
60 K
200 nm = 1138 μm



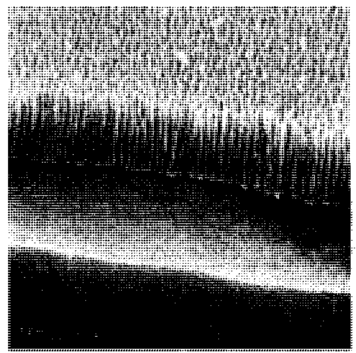
100 K
100 nm = 928 μm



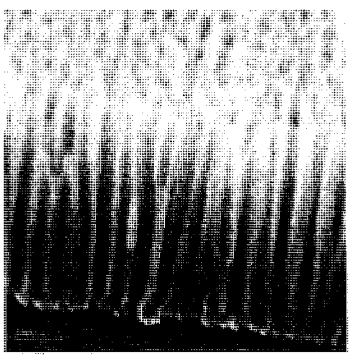
100 K
100 nm = 938 μm



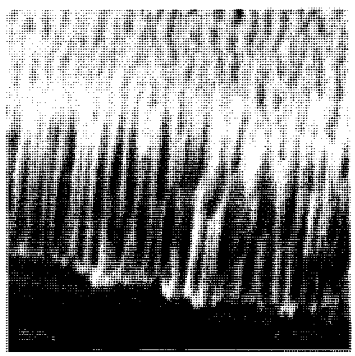
18 K
0.5 μm = 850 μm



25 K
500 nm = 1188 μm



35 K
200 nm = 650 μm



45 K
200 nm = 850 μm

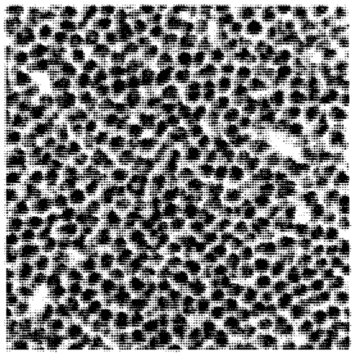
Diameter Measurements for Substrate 7								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	274	58.42	Diameter	295	62.90	Diameter	345	60.63
Diameter	277	59.06	Diameter	303	64.61	Diameter	363	63.80
Diameter	248	52.88	Diameter	311	66.31	Diameter	387	68.01
Diameter	298	63.54	Diameter	355	75.69	Diameter	289	50.79
Diameter	316	67.38	Diameter	352	75.05	Diameter	366	64.32
Diameter	287	61.19	Diameter	282	60.13	Diameter	383	67.31
Diameter	319	68.02	Diameter	332	70.79	Diameter	320	56.24
Diameter	326	69.51	Diameter	328	69.94	Diameter	360	63.27
Diameter	285	60.77	Diameter	320	68.23	Diameter	418	73.46
Diameter	365	77.83	Diameter	325	69.30	Diameter	393	69.07
Diameter	364	77.61	Diameter	350	74.63	Diameter	412	72.41
Diameter	343	73.13	Diameter	301	64.18	Diameter	301	52.90
Diameter	326	69.51	Diameter	347	73.99	Diameter	406	71.35
Diameter	308	65.67	Diameter	347	73.99	Diameter	388	68.19
Diameter	356	75.91	Diameter	307	65.46	Diameter	423	74.34
Diameter	279	59.49	Diameter	353	75.27	Diameter	266	46.75
Diameter	308	65.67	Diameter	313	66.74	Diameter	329	57.82
Diameter	293	62.47	Diameter	330	70.36	Diameter	348	61.16
Diameter	310	66.10	Diameter	338	72.07	Diameter	356	62.57
Diameter	319	68.02	Diameter	353	75.27	Diameter	430	75.57
Diameter	326	69.51	Diameter	352	75.05	Diameter	387	68.01
Diameter	329	70.15	Diameter	355	75.69	Diameter	380	66.78
Diameter	350	74.63	Diameter	342	72.92	Diameter	380	66.78
Diameter	377	80.38	Diameter	410	72.06	Diameter	379	66.61
Diameter	314	66.95	Diameter	416	73.11	Diameter	342	60.11
Diameter	330	70.36	Diameter	354	62.21	Diameter	384	67.49
Diameter	310	66.10	Diameter	363	63.80	Diameter	412	72.41
Diameter	305	65.03	Diameter	407	71.53	Diameter	382	67.14
Diameter	299	63.75	Diameter	442	77.68	Diameter	395	69.42
Diameter	353	75.27	Diameter	409	71.88	Diameter	429	75.40
Diameter	332	70.79	Diameter	390	68.54	Diameter	405	71.18
Diameter	296	63.11	Diameter	308	54.13	Diameter	367	64.50
Diameter	315	67.16	Diameter	342	60.11	Diameter	384	67.49
Diameter	317	67.59	Diameter	367	64.50	Diameter	299	52.55
Diameter	304	64.82	Diameter	392	68.89	Diameter	368	64.67
Diameter	330	70.36	Diameter	310	54.48	Diameter	443	77.86
Diameter	331	70.58	Diameter	354	62.21	Diameter	421	73.99
Diameter	315	67.16	Diameter	420	73.81	Diameter	427	75.04
Diameter	317	67.59	Diameter	450	79.09	Diameter	337	59.23
Diameter	277	59.06	Diameter	457	80.32	Diameter	421	73.99
Diameter	303	64.61	Diameter	352	61.86	Diameter	342	60.11

Diameter Measurements for Substrate 7								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	345	60.63	Diameter	611	65.14	Diameter	594	63.33
Diameter	435	76.45	Diameter	535	57.04	Diameter	432	46.06
Diameter	392	68.89	Diameter	528	56.29	Diameter	565	60.23
Diameter	400	70.30	Diameter	632	67.38	Diameter	560	59.70
Diameter	600	63.97	Diameter	551	58.74	Diameter	428	45.63
Diameter	569	60.66	Diameter	520	55.44	Diameter	633	67.48
Diameter	630	67.16	Diameter	726	77.40	Diameter	591	63.01
Diameter	517	55.12	Diameter	658	70.15	Diameter	614	65.46
Diameter	634	67.59	Diameter	538	57.36	Diameter	577	61.51
Diameter	819	87.31	Diameter	594	63.33	Diameter	508	54.16
Diameter	733	78.14	Diameter	591	63.01	Diameter	661	70.47
Diameter	667	71.11	Diameter	573	61.09	Diameter	705	75.16
Diameter	647	68.98	Diameter	680	72.49	Diameter	672	71.64
Diameter	596	63.54	Diameter	719	76.65	Diameter	632	67.38
Diameter	623	66.42	Diameter	650	69.30	Diameter	516	55.01
Diameter	530	56.50	Diameter	598	63.75			
Diameter	493	52.56	Diameter	498	53.09			
Diameter	474	50.53	Diameter	661	70.47			
Diameter	752	80.17	Diameter	590	62.90			
Diameter	645	68.76	Diameter	583	62.15			
Diameter	633	67.48	Diameter	652	69.51			
Diameter	662	70.58	Diameter	703	74.95			
Diameter	691	73.67	Diameter	624	66.52			
Diameter	613	65.35	Diameter	641	68.34			
Diameter	702	74.84	Diameter	651	69.40			
Diameter	596	63.54	Diameter	542	57.78			
Diameter	638	68.02	Diameter	557	59.38			
Diameter	623	66.42	Diameter	550	58.64			
Diameter	571	60.87	Diameter	610	65.03			
Diameter	582	62.05	Diameter	611	65.14			
Diameter	545	58.10	Diameter	549	58.53			
Diameter	560	59.70	Diameter	613	65.35			
Diameter	643	68.55	Diameter	473	50.43			
Diameter	503	53.62	Diameter	552	58.85			
Diameter	515	54.90	Diameter	661	70.47			
Diameter	543	57.89	Diameter	465	49.57			
Diameter	602	64.18	Diameter	431	45.95			
Diameter	453	48.29	Diameter	499	53.20			
Diameter	546	58.21	Diameter	547	58.32			
Diameter	643	68.55	Diameter	595	63.43			
Diameter	637	67.91	Diameter	508	54.16			

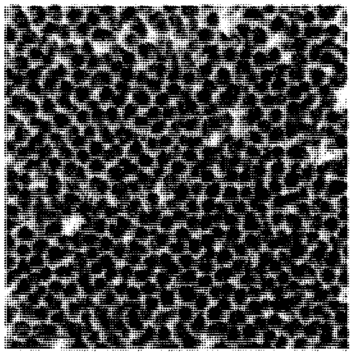
Nanopore Length Measurements for Substrate 7								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1451	853.53	Distance	1231	863.86	Distance	2896	891.08
Distance	1413	831.18	Distance	1250	877.19	Distance	2984	918.15
Distance	1439	846.47	Distance	1227	861.05	Distance	2966	912.62
Distance	1406	827.06	Distance	1231	863.86	Distance	2859	879.69
Distance	1338	787.06	Distance	1197	840.00	Distance	2801	861.85
Distance	1414	831.76	Distance	1217	854.04	Distance	2805	863.08
Distance	1428	840.00	Distance	1201	842.81	Distance	2812	865.23
Distance	1419	834.71	Distance	1225	859.65	Distance	3057	940.62
Distance	1440	847.06	Distance	1115	782.46	Distance	3006	924.92
Distance	1496	880.00	Distance	1265	887.72	Distance	3030	932.31
Distance	1500	882.35	Distance	1240	870.18	Distance	3185	980.00
Distance	1424	837.65	Distance	1233	865.26	Distance	2888	888.62
Distance	1500	882.35	Distance	1171	821.75	Distance	2916	897.23
Distance	1501	882.94	Distance	1157	811.93	Distance	2871	883.38
Distance	1404	825.88	Distance	1144	802.81	Distance	2737	842.15
Distance	1413	831.18	Distance	1178	826.67	Distance	2816	866.46
Distance	1453	854.71	Distance	1209	848.42	Distance	2694	828.92
Distance	1516	891.76	Distance	1162	815.44	Distance	2850	876.92
Distance	1464	861.18	Distance	1193	837.19	Distance	2796	860.31
Distance	1458	857.65	Distance	1134	795.79	Distance	2686	826.46
Distance	1430	841.18	Distance	1143	802.11	Distance	3616	850.82
Distance	1353	795.88	Distance	1204	844.91	Distance	3896	916.71
Distance	1318	775.29	Distance	1280	898.25	Distance	3895	916.47
Distance	1361	800.59	Distance	1194	837.89	Distance	3700	870.59
Distance	1355	797.06	Distance	1230	863.16	Distance	3597	846.35
Distance	1251	735.88	Distance	1202	843.51	Distance	3552	835.76
Distance	1338	787.06	Distance	1226	860.35	Distance	3580	842.35
Distance	1329	781.76	Distance	1290	905.26	Distance	3656	860.24
Distance	1313	772.35	Distance	1165	817.54	Distance	3393	798.35
Distance	1376	809.41	Distance	1223	858.25	Distance	3464	815.06
Distance	1401	824.12	Distance	1214	851.93	Distance	3221	757.88
Distance	1388	816.47	Distance	1113	781.05	Distance	3356	789.65
Distance	1401	824.12	Distance	1103	774.04	Distance	3566	839.06
Distance	1325	779.41	Distance	1121	786.67	Distance	3545	834.12
Distance	1313	772.35	Distance	1183	830.18	Distance	3355	789.41
Distance	1268	745.88	Distance	1174	823.86	Distance	2921	898.77
Distance	1292	760.00	Distance	1199	841.40	Distance	1197	840.00
Distance	1347	792.35	Distance	1248	875.79			
Distance	1244	872.98	Distance	1233	865.26			
Distance	1298	910.88	Distance	3202	985.23			
Distance	1256	881.40	Distance	3004	924.31			

Appendix I. Substrate 8 Data

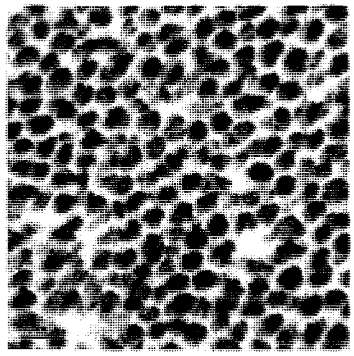
SEM Images for Substrate 8



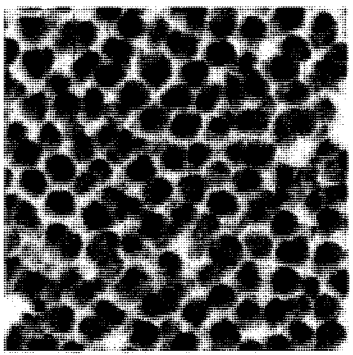
50 K
200 nm = 938 μm



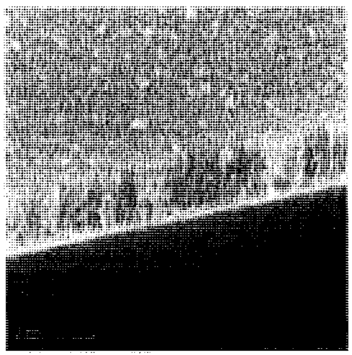
50 K
200 nm = 938 μm



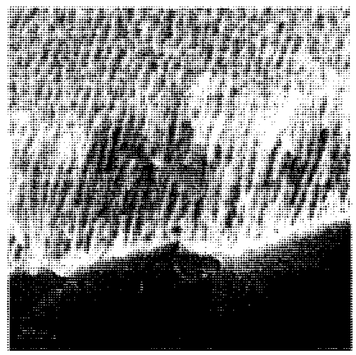
80 K
100 nm = 750 μm



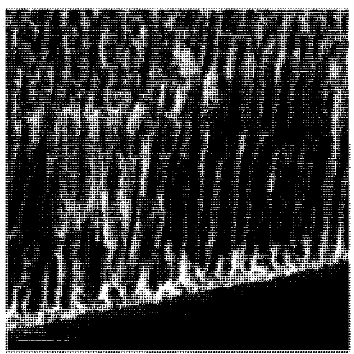
100 K
100 nm = 938 μm



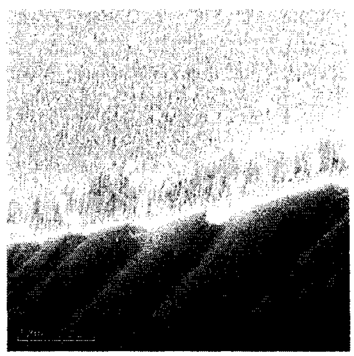
15 K
1 μm = 1425 μm



35 K
200 nm = 650 μm



50 K
200 nm = 938 μm



18 K
0.5 μm = 850 μm

Diameter Measurements for Substrate 8								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	239	50.96	Diameter	225	47.97	Diameter	229	48.83
Diameter	226	48.19	Diameter	250	53.30	Diameter	237	50.53
Diameter	261	55.65	Diameter	169	36.03	Diameter	346	73.77
Diameter	238	50.75	Diameter	232	49.47	Diameter	273	58.21
Diameter	240	51.17	Diameter	233	49.68	Diameter	262	55.86
Diameter	259	55.22	Diameter	244	52.03	Diameter	262	55.86
Diameter	259	55.22	Diameter	220	46.91	Diameter	269	57.36
Diameter	227	48.40	Diameter	237	50.53	Diameter	271	57.78
Diameter	238	50.75	Diameter	234	49.89	Diameter	244	52.03
Diameter	236	50.32	Diameter	205	43.71	Diameter	321	68.44
Diameter	227	48.40	Diameter	237	50.53	Diameter	227	48.40
Diameter	196	41.79	Diameter	239	50.96	Diameter	230	49.04
Diameter	248	52.88	Diameter	260	55.44	Diameter	266	56.72
Diameter	179	38.17	Diameter	268	57.14	Diameter	257	54.80
Diameter	245	52.24	Diameter	237	50.53	Diameter	254	54.16
Diameter	222	47.33	Diameter	226	48.19	Diameter	272	58.00
Diameter	240	51.17	Diameter	238	50.75	Diameter	265	56.50
Diameter	230	49.04	Diameter	238	50.75	Diameter	243	51.81
Diameter	229	48.83	Diameter	233	49.68	Diameter	273	58.21
Diameter	225	47.97	Diameter	261	55.65	Diameter	217	46.27
Diameter	260	55.44	Diameter	224	47.76	Diameter	293	62.47
Diameter	234	49.89	Diameter	259	55.22	Diameter	265	56.50
Diameter	230	49.04	Diameter	296	63.11	Diameter	266	56.72
Diameter	217	46.27	Diameter	230	49.04	Diameter	260	55.44
Diameter	237	50.53	Diameter	248	52.88	Diameter	295	62.90
Diameter	259	55.22	Diameter	233	49.68	Diameter	269	57.36
Diameter	208	44.35	Diameter	254	54.16	Diameter	293	62.47
Diameter	219	46.70	Diameter	259	55.22	Diameter	239	50.96
Diameter	237	50.53	Diameter	268	57.14	Diameter	257	54.80
Diameter	237	50.53	Diameter	213	45.42	Diameter	293	62.47
Diameter	217	46.27	Diameter	281	59.91	Diameter	246	52.45
Diameter	217	46.27	Diameter	255	54.37	Diameter	292	62.26
Diameter	268	57.14	Diameter	212	45.20	Diameter	271	57.78
Diameter	247	52.67	Diameter	277	59.06	Diameter	283	60.34
Diameter	221	47.12	Diameter	244	52.03	Diameter	224	47.76
Diameter	217	46.27	Diameter	229	48.83	Diameter	264	56.29
Diameter	240	51.17	Diameter	226	48.19	Diameter	244	52.03
Diameter	261	55.65	Diameter	200	42.64	Diameter	258	55.01
Diameter	242	51.60	Diameter	213	45.42	Diameter	252	53.73
Diameter	208	44.35	Diameter	252	53.73	Diameter	283	60.34
Diameter	227	48.40	Diameter	244	52.03	Diameter	238	50.75

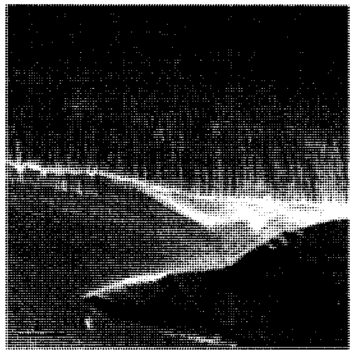
Diameter Measurements for Substrate 8								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	268	57.14	Diameter	361	48.13	Diameter	488	52.03
Diameter	239	50.96	Diameter	391	52.13	Diameter	357	38.06
Diameter	262	55.86	Diameter	332	44.27	Diameter	525	55.97
Diameter	291	62.05	Diameter	397	52.93	Diameter	410	43.71
Diameter	302	40.27	Diameter	291	38.80	Diameter	418	44.56
Diameter	326	43.47	Diameter	380	50.67	Diameter	427	45.52
Diameter	257	34.27	Diameter	349	46.53	Diameter	474	50.53
Diameter	331	44.13	Diameter	395	52.67	Diameter	519	55.33
Diameter	352	46.93	Diameter	407	54.27	Diameter	419	44.67
Diameter	274	36.53	Diameter	280	37.33	Diameter	594	63.33
Diameter	266	35.47	Diameter	435	58.00	Diameter	317	33.80
Diameter	356	47.47	Diameter	316	42.13	Diameter	428	45.63
Diameter	359	47.87	Diameter	400	53.33	Diameter	436	46.48
Diameter	377	50.27	Diameter	396	52.80	Diameter	438	46.70
Diameter	338	45.07	Diameter	366	48.80	Diameter	456	48.61
Diameter	312	41.60	Diameter	432	57.60	Diameter	499	53.20
Diameter	432	57.60	Diameter	389	51.87	Diameter	390	41.58
Diameter	278	37.07	Diameter	359	47.87	Diameter	365	38.91
Diameter	343	45.73	Diameter	415	55.33	Diameter	336	35.82
Diameter	296	39.47	Diameter	398	53.07	Diameter	494	52.67
Diameter	372	49.60	Diameter	353	47.07	Diameter	469	50.00
Diameter	273	36.40	Diameter	378	50.40	Diameter	495	52.77
Diameter	313	41.73	Diameter	386	51.47	Diameter	420	44.78
Diameter	266	35.47	Diameter	362	48.27	Diameter	490	52.24
Diameter	317	42.27	Diameter	338	45.07	Diameter	452	48.19
Diameter	413	55.07	Diameter	346	46.13	Diameter	511	54.48
Diameter	312	41.60	Diameter	268	35.73	Diameter	526	56.08
Diameter	375	50.00	Diameter	473	50.43	Diameter	481	51.28
Diameter	365	48.67	Diameter	398	42.43	Diameter	477	50.85
Diameter	332	44.27	Diameter	477	50.85	Diameter	427	45.52
Diameter	290	38.67	Diameter	491	52.35	Diameter	444	47.33
Diameter	458	61.07	Diameter	456	48.61	Diameter	505	53.84
Diameter	338	45.07	Diameter	351	37.42	Diameter	475	50.64
Diameter	382	50.93	Diameter	438	46.70	Diameter	407	43.39
Diameter	262	34.93	Diameter	422	44.99	Diameter	335	35.71
Diameter	304	40.53	Diameter	390	41.58	Diameter	421	44.88
Diameter	320	42.67	Diameter	383	40.83	Diameter	439	46.80
Diameter	433	57.73	Diameter	428	45.63	Diameter	400	42.64
Diameter	313	41.73	Diameter	407	43.39	Diameter	500	53.30
Diameter	213	28.40	Diameter	357	38.06	Diameter	536	57.14
Diameter	364	48.53	Diameter	380	40.51	Diameter	421	44.88

Nanopore Length Measurements for Substrate 8								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1027	720.70	Distance	2228	685.54	Distance	821	576.14
Distance	1039	729.12	Distance	2214	681.23	Distance	862	604.91
Distance	1001	702.46	Distance	2300	707.69	Distance	924	648.42
Distance	1061	744.56	Distance	2342	720.62	Distance	944	662.46
Distance	1121	786.67	Distance	2359	725.85	Distance	845	592.98
Distance	938	658.25	Distance	2358	725.54	Distance	844	592.28
Distance	925	649.12	Distance	2265	696.92	Distance	878	616.14
Distance	1005	705.26	Distance	2406	740.31	Distance	868	609.12
Distance	1007	706.67	Distance	2164	665.85	Distance	724	508.07
Distance	1069	750.18	Distance	2218	682.46	Distance	850	596.49
Distance	1115	782.46	Distance	2234	687.38	Distance	803	563.51
Distance	1004	704.56	Distance	3664	781.24	Distance	816	572.63
Distance	1065	747.37	Distance	3944	840.94	Distance	844	592.28
Distance	1098	770.53	Distance	3689	786.57	Distance	783	549.47
Distance	1033	724.91	Distance	3632	774.41	Distance	800	561.40
Distance	1019	715.09	Distance	4307	918.34	Distance	762	534.74
Distance	1013	710.88	Distance	3088	658.42	Distance	772	541.75
Distance	1026	720.00	Distance	4908	1046.48	Distance	885	621.05
Distance	1055	740.35	Distance	3513	749.04	Distance	942	661.05
Distance	1527	1071.58	Distance	3281	699.57	Distance	934	655.44
Distance	977	685.61	Distance	3355	715.35	Distance	892	625.96
Distance	974	683.51	Distance	3458	737.31	Distance	879	616.84
Distance	1009	708.07	Distance	3305	704.69	Distance	919	644.91
Distance	889	623.86	Distance	3378	720.26	Distance	845	592.98
Distance	979	687.02	Distance	3399	724.73	Distance	1117	783.86
Distance	962	675.09	Distance	3195	681.24	Distance	817	573.33
Distance	1014	711.58	Distance	3307	705.12	Distance	770	540.35
Distance	985	691.23	Distance	3456	736.89	Distance	852	597.89
Distance	1111	779.65	Distance	3626	773.13	Distance	2208	679.38
Distance	1067	748.77	Distance	4695	1001.07			
Distance	2558	787.08	Distance	919	644.91			
Distance	2516	774.15	Distance	807	566.32			
Distance	2484	764.31	Distance	834	585.26			
Distance	2593	797.85	Distance	864	606.32			
Distance	2547	783.69	Distance	827	580.35			
Distance	2676	823.38	Distance	859	602.81			
Distance	2693	828.62	Distance	767	538.25			
Distance	2580	793.85	Distance	752	527.72			
Distance	2645	813.85	Distance	710	498.25			
Distance	2643	813.23	Distance	827	580.35			
Distance	2567	789.85	Distance	871	611.23			

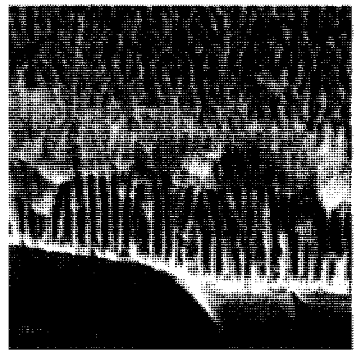
Appendix J. Center Point 1 Substrate Data

SEM Images for Center Point 1 Substrate

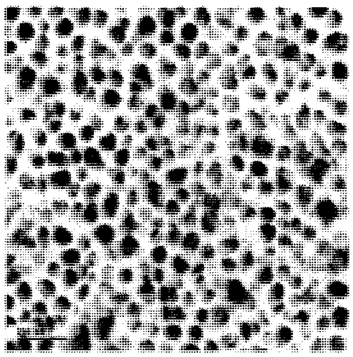
50 K
200 nm = 938 μm



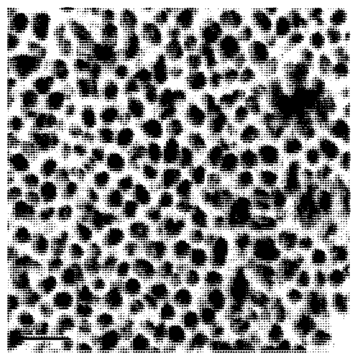
50 K
200 nm = 938 μm



20 K
500 nm = 938 μm



20 K
500 nm = 938 μm



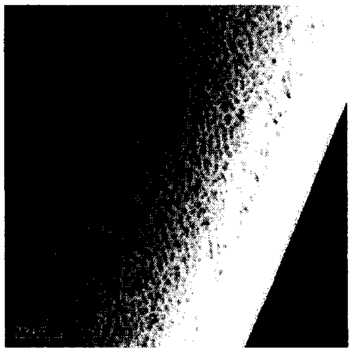
30 K
500 nm = 1425 μm

Diameter Measurements for Center Point Run 1								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	344	73.35	Diameter	303	64.61	Diameter	241	51.39
Diameter	322	68.66	Diameter	279	59.49	Diameter	384	81.88
Diameter	316	67.38	Diameter	350	74.63	Diameter	303	64.61
Diameter	294	62.69	Diameter	270	57.57	Diameter	282	60.13
Diameter	345	73.56	Diameter	388	82.73	Diameter	304	64.82
Diameter	337	71.86	Diameter	304	64.82	Diameter	323	68.87
Diameter	354	75.48	Diameter	304	64.82	Diameter	385	82.09
Diameter	305	65.03	Diameter	306	65.25	Diameter	342	72.92
Diameter	334	71.22	Diameter	285	60.77	Diameter	251	53.52
Diameter	275	58.64	Diameter	309	65.88	Diameter	329	70.15
Diameter	243	51.81	Diameter	318	67.80	Diameter	323	68.87
Diameter	279	59.49	Diameter	337	71.86	Diameter	333	71.00
Diameter	306	65.25	Diameter	318	67.80	Diameter	282	60.13
Diameter	287	61.19	Diameter	310	66.10	Diameter	266	56.72
Diameter	298	63.54	Diameter	339	72.28	Diameter	332	70.79
Diameter	397	84.65	Diameter	275	58.64	Diameter	261	55.65
Diameter	309	65.88	Diameter	277	59.06	Diameter	337	71.86
Diameter	273	58.21	Diameter	306	65.25	Diameter	334	71.22
Diameter	318	67.80	Diameter	294	62.69	Diameter	277	59.06
Diameter	302	64.39	Diameter	255	54.37	Diameter	298	63.54
Diameter	266	56.72	Diameter	254	54.16	Diameter	350	74.63
Diameter	321	68.44	Diameter	319	68.02	Diameter	297	63.33
Diameter	298	63.54	Diameter	286	60.98	Diameter	338	72.07
Diameter	327	69.72	Diameter	337	71.86	Diameter	310	66.10
Diameter	294	62.69	Diameter	308	65.67	Diameter	305	65.03
Diameter	302	64.39	Diameter	303	64.61	Diameter	383	81.66
Diameter	267	56.93	Diameter	265	56.50	Diameter	304	64.82
Diameter	360	76.76	Diameter	301	64.18	Diameter	253	53.94
Diameter	333	71.00	Diameter	298	63.54	Diameter	238	50.75
Diameter	321	68.44	Diameter	318	67.80	Diameter	338	72.07
Diameter	319	68.02	Diameter	347	73.99	Diameter	302	64.39
Diameter	304	64.82	Diameter	207	44.14	Diameter	302	64.39
Diameter	375	79.96	Diameter	295	62.90	Diameter	300	63.97
Diameter	300	63.97	Diameter	384	81.88	Diameter	305	65.03
Diameter	335	71.43	Diameter	279	59.49	Diameter	337	71.86
Diameter	325	69.30	Diameter	271	57.78	Diameter	285	60.77
Diameter	359	76.55	Diameter	288	61.41	Diameter	364	77.61
Diameter	282	60.13	Diameter	406	86.57	Diameter	288	61.41
Diameter	355	75.69	Diameter	249	53.09	Diameter	317	67.59
Diameter	345	73.56	Diameter	303	64.61	Diameter	325	69.30
Diameter	354	75.48	Diameter	274	58.42	Diameter	293	62.47

Nanopore Length Measurements for Center Point Run 1					
Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	1380	735.61	Distance	1237	659.38
Distance	1451	773.45	Distance	1241	661.51
Distance	1199	639.13	Distance	1222	651.39
Distance	1180	629.00	Distance	1328	707.89
Distance	1257	670.04	Distance	1402	747.33
Distance	1413	753.20	Distance	2352	825.26
Distance	1354	721.75	Distance	2148	753.68
Distance	1312	699.36	Distance	2366	830.18
Distance	1315	700.96	Distance	2182	765.61
Distance	1340	714.29	Distance	2204	773.33
Distance	1488	793.18	Distance	2190	768.42
Distance	1505	802.24	Distance	2151	754.74
Distance	1538	819.83	Distance	2128	746.67
Distance	1438	766.52	Distance	2202	772.63
Distance	1544	823.03	Distance	2190	768.42
Distance	1526	813.43	Distance	1923	674.74
Distance	1379	735.07	Distance	2355	826.32
Distance	1447	771.32	Distance	2176	763.51
Distance	1463	779.85	Distance	2315	812.28
Distance	1381	736.14	Distance	2359	827.72
Distance	1412	752.67	Distance	1322	704.69
Distance	1387	739.34			
Distance	1500	799.57			
Distance	1438	766.52			
Distance	1450	772.92			
Distance	1401	746.80			
Distance	1463	779.85			
Distance	1438	766.52			
Distance	1413	753.20			
Distance	1433	763.86			
Distance	1399	745.74			
Distance	1326	706.82			
Distance	1250	666.31			
Distance	1200	639.66			
Distance	1291	688.17			
Distance	1189	633.80			
Distance	1411	752.13			
Distance	1425	759.59			
Distance	1306	696.16			
Distance	1391	741.47			

Appendix K. Center Point Repeatability Substrate Data

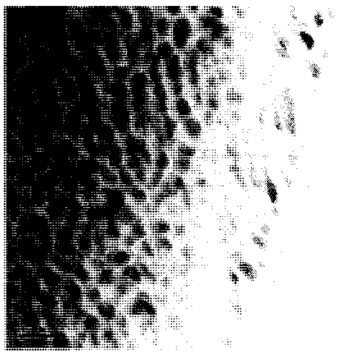
SEM Images for Center Point Repeatability Substrate



18 K
0.5 μm = 850 μm

35 K
200 nm = 650 μm

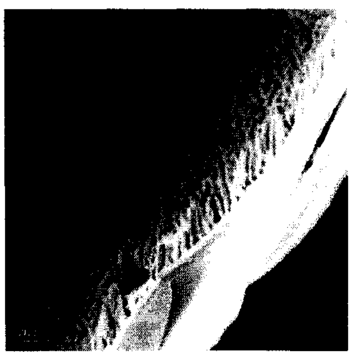
20 K
500 nm = 938 μm



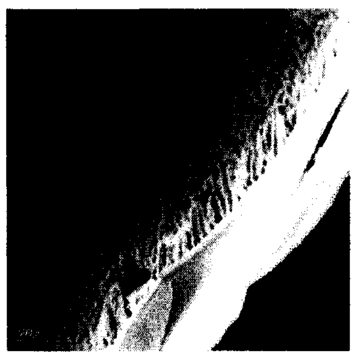
50 K
200 nm = 938 μm

15 K
1 μm = 1425 μm

18 K
0.5 μm = 850 μm



20 K
500 nm = 938 μm



11 K
2 μm = 1038 μm

Diameter Measurements for Center Point Repeatability Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	110	46.30	Diameter	108	45.45	Diameter	319	68.02
Diameter	88	37.04	Diameter	99	41.67	Diameter	304	64.82
Diameter	91	38.30	Diameter	100	42.09	Diameter	270	57.57
Diameter	96	40.40	Diameter	114	47.98	Diameter	248	52.88
Diameter	103	43.35	Diameter	109	45.88	Diameter	272	58.00
Diameter	101	42.51	Diameter	121	50.93	Diameter	297	63.33
Diameter	91	38.30	Diameter	134	56.40	Diameter	327	69.72
Diameter	91	38.30	Diameter	126	53.03	Diameter	257	54.80
Diameter	107	45.03	Diameter	103	43.35	Diameter	280	59.70
Diameter	90	37.88	Diameter	109	45.88	Diameter	298	63.54
Diameter	105	44.19	Diameter	119	50.08	Diameter	247	52.67
Diameter	113	47.56	Diameter	91	38.30	Diameter	298	63.54
Diameter	107	45.03	Diameter	120	50.51	Diameter	246	52.45
Diameter	103	43.35	Diameter	113	47.56	Diameter	198	42.22
Diameter	113	47.56	Diameter	159	66.92	Diameter	235	50.11
Diameter	113	47.56	Diameter	119	50.08	Diameter	242	51.60
Diameter	135	56.82	Diameter	98	41.25	Diameter	241	51.39
Diameter	120	50.51	Diameter	131	55.13	Diameter	298	63.54
Diameter	85	35.77	Diameter	105	44.19	Diameter	308	65.67
Diameter	93	39.14	Diameter	131	55.13	Diameter	302	64.39
Diameter	136	57.24	Diameter	101	42.51	Diameter	316	67.38
Diameter	96	40.40	Diameter	103	43.35	Diameter	283	60.34
Diameter	88	37.04	Diameter	106	44.61	Diameter	281	59.91
Diameter	112	47.14	Diameter	107	45.03	Diameter	248	52.88
Diameter	106	44.61	Diameter	108	45.45	Diameter	320	68.23
Diameter	126	53.03	Diameter	221	47.12	Diameter	246	52.45
Diameter	102	42.93	Diameter	253	53.94	Diameter	276	58.85
Diameter	116	48.82	Diameter	234	49.89	Diameter	266	56.72
Diameter	118	49.66	Diameter	253	53.94	Diameter	314	66.95
Diameter	114	47.98	Diameter	238	50.75	Diameter	262	55.86
Diameter	121	50.93	Diameter	295	62.90	Diameter	320	68.23
Diameter	111	46.72	Diameter	199	42.43	Diameter	278	59.28
Diameter	85	35.77	Diameter	251	53.52	Diameter	255	54.37
Diameter	123	51.77	Diameter	236	50.32	Diameter	251	53.52
Diameter	128	53.87	Diameter	244	52.03	Diameter	230	49.04
Diameter	116	48.82	Diameter	241	51.39	Diameter	264	56.29
Diameter	113	47.56	Diameter	269	57.36	Diameter	284	60.55
Diameter	131	55.13	Diameter	220	46.91	Diameter	310	66.10
Diameter	106	44.61	Diameter	275	58.64	Diameter	277	59.06
Diameter	112	47.14	Diameter	275	58.64	Diameter	244	52.03

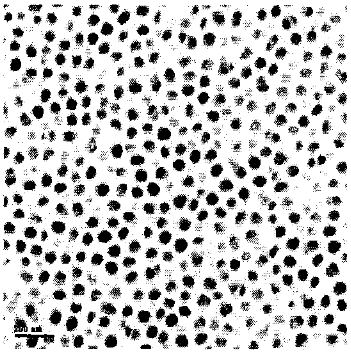
Diameter Measurements for Center Point Repeatability Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	308	65.67	Diameter	121	64.50	Diameter	233	49.68
Diameter	265	56.50	Diameter	111	59.17	Diameter	241	51.39
Diameter	284	60.55	Diameter	85	45.31	Diameter	193	41.15
Diameter	335	71.43	Diameter	123	65.57	Diameter	199	42.43
Diameter	293	62.47	Diameter	128	68.23	Diameter	177	37.74
Diameter	286	60.98	Diameter	116	61.83	Diameter	188	40.09
Diameter	336	71.64	Diameter	113	60.23	Diameter	221	47.12
Diameter	331	70.58	Diameter	131	69.83	Diameter	189	40.30
Diameter	358	76.33	Diameter	106	56.50	Diameter	230	49.04
Diameter	253	53.94	Diameter	112	59.70	Diameter	216	46.06
Diameter	110	58.64	Diameter	108	57.57	Diameter	199	42.43
Diameter	88	46.91	Diameter	99	52.77	Diameter	244	52.03
Diameter	91	48.51	Diameter	100	53.30	Diameter	214	45.63
Diameter	96	51.17	Diameter	114	60.77	Diameter	197	42.00
Diameter	103	54.90	Diameter	109	58.10	Diameter	186	39.66
Diameter	101	53.84	Diameter	121	64.50	Diameter	227	48.40
Diameter	91	48.51	Diameter	134	71.43	Diameter	194	41.36
Diameter	91	48.51	Diameter	126	67.16	Diameter	217	46.27
Diameter	107	57.04	Diameter	103	54.90	Diameter	219	46.70
Diameter	90	47.97	Diameter	109	58.10	Diameter	195	41.58
Diameter	105	55.97	Diameter	119	63.43	Diameter	241	51.39
Diameter	113	60.23	Diameter	91	48.51	Diameter	204	43.50
Diameter	107	57.04	Diameter	120	63.97	Diameter	202	43.07
Diameter	103	54.90	Diameter	113	60.23	Diameter	197	42.00
Diameter	113	60.23	Diameter	159	84.75	Diameter	224	47.76
Diameter	113	60.23	Diameter	119	63.43	Diameter	190	40.51
Diameter	135	71.96	Diameter	98	52.24	Diameter	247	52.67
Diameter	120	63.97	Diameter	131	69.83	Diameter	262	55.86
Diameter	85	45.31	Diameter	105	55.97	Diameter	227	48.40
Diameter	93	49.57	Diameter	131	69.83	Diameter	264	56.29
Diameter	136	72.49	Diameter	101	53.84	Diameter	275	58.64
Diameter	96	51.17	Diameter	103	54.90	Diameter	288	61.41
Diameter	88	46.91	Diameter	106	56.50	Diameter	258	55.01
Diameter	112	59.70	Diameter	107	57.04	Diameter	216	46.06
Diameter	106	56.50	Diameter	108	57.57	Diameter	273	58.21
Diameter	126	67.16	Diameter	194	41.36	Diameter	269	57.36
Diameter	102	54.37	Diameter	153	32.62	Diameter	250	53.30
Diameter	116	61.83	Diameter	202	43.07	Diameter	222	47.33
Diameter	118	62.90	Diameter	197	42.00	Diameter	244	52.03
Diameter	114	60.77	Diameter	195	41.58	Diameter	257	54.80

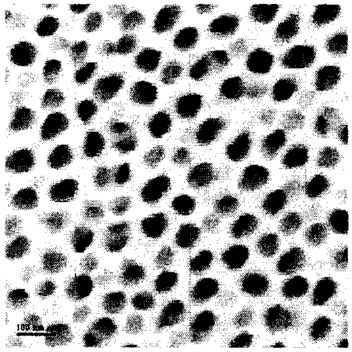
Nanopore Length Measurements for Center Point Repeatability Run

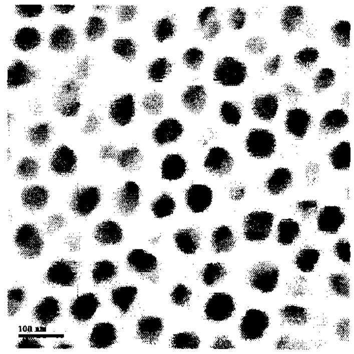
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	488	650.67	Distance	485	538.89	Distance	416	801.54
Distance	439	585.33	Distance	551	612.22	Distance	353	680.15
Distance	532	709.33	Distance	585	650.00	Distance	331	637.76
Distance	476	634.67	Distance	470	522.22	Distance	321	618.50
Distance	475	633.33	Distance	675	719.62	Distance	325	626.20
Distance	488	650.67	Distance	721	768.66	Distance	263	506.74
Distance	465	620.00	Distance	642	684.43	Distance	280	539.50
Distance	478	637.33	Distance	713	760.13	Distance	276	531.79
Distance	453	604.00	Distance	750	799.57	Distance	325	626.20
Distance	483	644.00	Distance	630	671.64	Distance	347	668.59
Distance	465	620.00	Distance	783	834.75	Distance	341	657.03
Distance	444	592.00	Distance	652	695.10	Distance	289	556.84
Distance	504	672.00	Distance	692	737.74			
Distance	521	694.67	Distance	643	685.50			
Distance	422	562.67	Distance	631	672.71			
Distance	427	569.33	Distance	775	826.23			
Distance	405	540.00	Distance	603	642.86			
Distance	431	574.67	Distance	663	706.82			
Distance	475	633.33	Distance	658	701.49			
Distance	549	610.00	Distance	773	824.09			
Distance	588	653.33	Distance	513	546.91			
Distance	541	601.11	Distance	744	793.18			
Distance	608	675.56	Distance	664	707.89			
Distance	559	621.11	Distance	711	758.00			
Distance	643	714.44	Distance	542	577.83			
Distance	500	555.56	Distance	502	535.18			
Distance	528	586.67	Distance	614	654.58			
Distance	694	771.11	Distance	365	703.28			
Distance	661	734.44	Distance	281	541.43			
Distance	606	673.33	Distance	338	651.25			
Distance	658	731.11	Distance	285	549.13			
Distance	639	710.00	Distance	306	589.60			
Distance	508	564.44	Distance	346	666.67			
Distance	490	544.44	Distance	399	768.79			
Distance	576	640.00	Distance	381	734.10			
Distance	628	697.78	Distance	359	691.71			
Distance	612	680.00	Distance	363	699.42			
Distance	516	573.33	Distance	275	529.87			
Distance	529	587.78	Distance	341	657.03			
Distance	463	514.44	Distance	403	776.49			

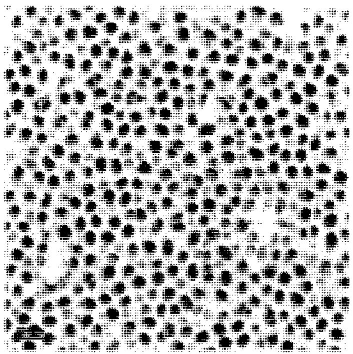
Appendix L. Center Point Reproducibility Substrate Data

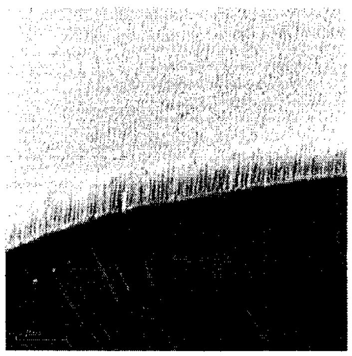
SEM Images for Center Point Reproducibility Substrate

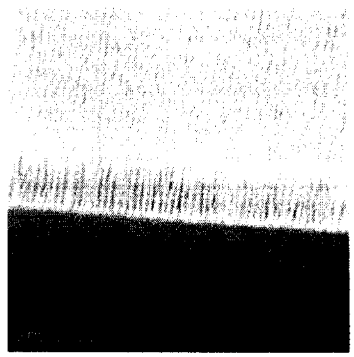

40 K
200 nm = 750 μm

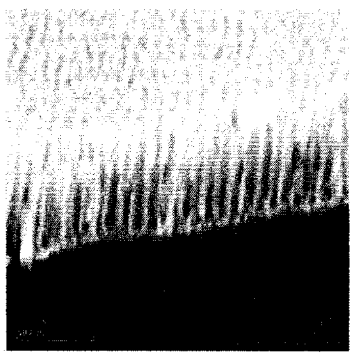

80 K
100 nm = 750 μm

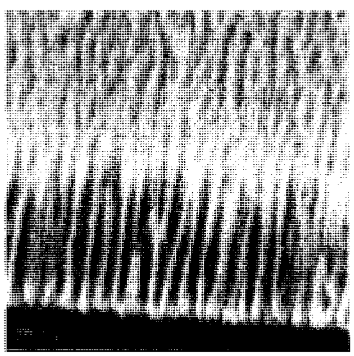

90 K
100 nm = 850 μm


40 K
200 nm = 750 μm


10 K
1 μm = 1038 μm


15 K
1 μm = 1425 μm


30 K
500 nm = 1425 μm


40 K
200 nm = 750 μm

Diameter Measurements for Center Point Reproducibility Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	206	54.93	Diameter	209	55.73	Diameter	409	54.53
Diameter	236	62.93	Diameter	239	63.73	Diameter	358	47.73
Diameter	211	56.27	Diameter	261	69.60	Diameter	393	52.40
Diameter	216	57.60	Diameter	214	57.07	Diameter	409	54.53
Diameter	214	57.07	Diameter	231	61.60	Diameter	390	52.00
Diameter	214	57.07	Diameter	229	61.07	Diameter	413	55.07
Diameter	197	52.53	Diameter	211	56.27	Diameter	435	58.00
Diameter	227	60.53	Diameter	249	66.40	Diameter	414	55.20
Diameter	236	62.93	Diameter	228	60.80	Diameter	389	51.87
Diameter	230	61.33	Diameter	201	53.60	Diameter	439	58.53
Diameter	231	61.60	Diameter	214	57.07	Diameter	427	56.93
Diameter	228	60.80	Diameter	199	53.07	Diameter	419	55.87
Diameter	258	68.80	Diameter	218	58.13	Diameter	408	54.40
Diameter	222	59.20	Diameter	221	58.93	Diameter	392	52.27
Diameter	223	59.47	Diameter	244	65.07	Diameter	429	57.20
Diameter	200	53.33	Diameter	254	67.73	Diameter	364	48.53
Diameter	216	57.60	Diameter	233	62.13	Diameter	431	57.47
Diameter	201	53.60	Diameter	256	68.27	Diameter	458	61.07
Diameter	202	53.87	Diameter	266	70.93	Diameter	406	54.13
Diameter	219	58.40	Diameter	254	67.73	Diameter	377	50.27
Diameter	199	53.07	Diameter	256	68.27	Diameter	480	64.00
Diameter	221	58.93	Diameter	249	66.40	Diameter	451	60.13
Diameter	210	56.00	Diameter	236	62.93	Diameter	378	50.40
Diameter	238	63.47	Diameter	257	68.53	Diameter	403	53.73
Diameter	238	63.47	Diameter	261	69.60	Diameter	427	56.93
Diameter	230	61.33	Diameter	434	57.87	Diameter	389	51.87
Diameter	251	66.93	Diameter	400	53.33	Diameter	393	52.40
Diameter	214	57.07	Diameter	409	54.53	Diameter	452	60.27
Diameter	218	58.13	Diameter	388	51.73	Diameter	397	52.93
Diameter	225	60.00	Diameter	349	46.53	Diameter	419	55.87
Diameter	227	60.53	Diameter	457	60.93	Diameter	379	50.53
Diameter	250	66.67	Diameter	468	62.40	Diameter	370	49.33
Diameter	240	64.00	Diameter	450	60.00	Diameter	463	61.73
Diameter	204	54.40	Diameter	471	62.80	Diameter	403	53.73
Diameter	250	66.67	Diameter	428	57.07	Diameter	401	53.47
Diameter	253	67.47	Diameter	427	56.93	Diameter	390	52.00
Diameter	240	64.00	Diameter	412	54.93	Diameter	412	54.93
Diameter	266	70.93	Diameter	473	63.07	Diameter	398	53.07
Diameter	227	60.53	Diameter	451	60.13	Diameter	390	52.00
Diameter	224	59.73	Diameter	415	55.33	Diameter	386	51.47

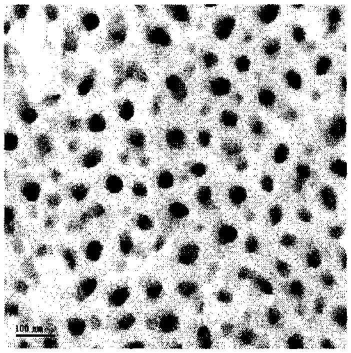
Diameter Measurements for Center Point Reproducibility Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	428	57.07	Diameter	511	60.12	Diameter	239	63.73
Diameter	410	54.67	Diameter	415	48.82	Diameter	169	45.07
Diameter	432	57.60	Diameter	535	62.94	Diameter	193	51.47
Diameter	426	56.80	Diameter	444	52.24	Diameter	252	67.20
Diameter	383	51.07	Diameter	435	51.18	Diameter	225	60.00
Diameter	404	53.87	Diameter	460	54.12	Diameter	188	50.13
Diameter	407	54.27	Diameter	444	52.24	Diameter	196	52.27
Diameter	395	52.67	Diameter	420	49.41	Diameter	226	60.27
Diameter	393	52.40	Diameter	434	51.06	Diameter	211	56.27
Diameter	433	57.73	Diameter	414	48.71	Diameter	211	56.27
Diameter	442	52.00	Diameter	476	56.00	Diameter	205	54.67
Diameter	416	48.94	Diameter	456	53.65	Diameter	208	55.47
Diameter	378	44.47	Diameter	430	50.59	Diameter	191	50.93
Diameter	463	54.47	Diameter	480	56.47	Diameter	209	55.73
Diameter	488	57.41	Diameter	455	53.53	Diameter	214	57.07
Diameter	438	51.53	Diameter	423	49.76	Diameter	191	50.93
Diameter	512	60.24	Diameter	454	53.41	Diameter	232	61.87
Diameter	448	52.71	Diameter	471	55.41	Diameter	192	51.20
Diameter	434	51.06	Diameter	493	58.00	Diameter	196	52.27
Diameter	426	50.12	Diameter	471	55.41	Diameter	193	51.47
Diameter	493	58.00	Diameter	418	49.18	Diameter	208	55.47
Diameter	419	49.29	Diameter	434	51.06	Diameter	203	54.13
Diameter	553	65.06	Diameter	428	50.35	Diameter	231	61.60
Diameter	452	53.18	Diameter	442	52.00	Diameter	194	51.73
Diameter	408	48.00	Diameter	495	58.24	Diameter	211	56.27
Diameter	529	62.24	Diameter	482	56.71	Diameter	211	56.27
Diameter	455	53.53	Diameter	492	57.88	Diameter	191	50.93
Diameter	451	53.06	Diameter	463	54.47	Diameter	205	54.67
Diameter	434	51.06	Diameter	434	51.06	Diameter	228	60.80
Diameter	458	53.88	Diameter	453	53.29	Diameter	203	54.13
Diameter	454	53.41	Diameter	506	59.53	Diameter	198	52.80
Diameter	514	60.47	Diameter	499	58.71	Diameter	204	54.40
Diameter	393	46.24	Diameter	479	56.35	Diameter	239	63.73
Diameter	507	59.65	Diameter	479	56.35	Diameter	213	56.80
Diameter	459	54.00	Diameter	484	56.94	Diameter	224	59.73
Diameter	453	53.29	Diameter	216	57.60	Diameter	221	58.93
Diameter	493	58.00	Diameter	214	57.07	Diameter	223	59.47
Diameter	542	63.76	Diameter	232	61.87	Diameter	208	55.47
Diameter	425	50.00	Diameter	225	60.00	Diameter	241	64.27
Diameter	451	53.06	Diameter	231	61.60	Diameter	192	51.20

Nanopore Length Measurements for Center Point Reproducibility Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	665	640.66	Distance	588	566.47	Distance	902	632.98
Distance	645	621.39	Distance	551	530.83	Distance	925	649.12
Distance	591	569.36	Distance	926	649.82	Distance	937	657.54
Distance	575	553.95	Distance	998	700.35	Distance	928	651.23
Distance	631	607.90	Distance	925	649.12	Distance	902	632.98
Distance	656	631.98	Distance	873	612.63	Distance	889	623.86
Distance	675	650.29	Distance	853	598.60	Distance	951	667.37
Distance	638	614.64	Distance	874	613.33	Distance	1880	659.65
Distance	678	653.18	Distance	838	588.07	Distance	1776	623.16
Distance	625	602.12	Distance	804	564.21	Distance	1888	662.46
Distance	603	580.92	Distance	932	654.04	Distance	1748	613.33
Distance	654	630.06	Distance	899	630.88	Distance	1733	608.07
Distance	615	592.49	Distance	945	663.16	Distance	1808	634.39
Distance	627	604.05	Distance	979	687.02	Distance	1840	645.61
Distance	665	640.66	Distance	981	688.42	Distance	1700	596.49
Distance	676	651.25	Distance	949	665.96	Distance	1744	611.93
Distance	602	579.96	Distance	968	679.30	Distance	1705	598.25
Distance	628	605.01	Distance	940	659.65	Distance	1697	595.44
Distance	563	542.39	Distance	1027	720.70	Distance	1680	589.47
Distance	639	615.61	Distance	1033	724.91	Distance	1653	580.00
Distance	638	614.64	Distance	965	677.19	Distance	1664	583.86
Distance	614	591.52	Distance	980	687.72	Distance	1623	569.47
Distance	616	593.45	Distance	944	662.46	Distance	1740	610.53
Distance	588	566.47	Distance	951	667.37	Distance	1679	589.12
Distance	650	626.20	Distance	932	654.04	Distance	1842	646.32
Distance	679	654.14	Distance	888	623.16	Distance	1764	618.95
Distance	653	629.09	Distance	954	669.47	Distance	1797	630.53
Distance	627	604.05	Distance	896	628.77	Distance	1851	649.47
Distance	627	604.05	Distance	927	650.53	Distance	1685	591.23
Distance	600	578.03	Distance	879	616.84	Distance	1737	609.47
Distance	625	602.12	Distance	875	614.04	Distance	1728	606.32
Distance	552	531.79	Distance	819	574.74	Distance	1622	569.12
Distance	614	591.52	Distance	880	617.54	Distance	1585	556.14
Distance	638	614.64	Distance	834	585.26	Distance	1622	569.12
Distance	627	604.05	Distance	859	602.81	Distance	2768	738.13
Distance	627	604.05	Distance	925	649.12	Distance	2642	704.53
Distance	615	592.49	Distance	845	592.98	Distance	2667	711.20
Distance	647	623.31	Distance	913	640.70	Distance	2642	704.53
Distance	585	563.58	Distance	972	682.11	Distance	2716	724.27
Distance	552	531.79	Distance	856	600.70	Distance	2656	708.27

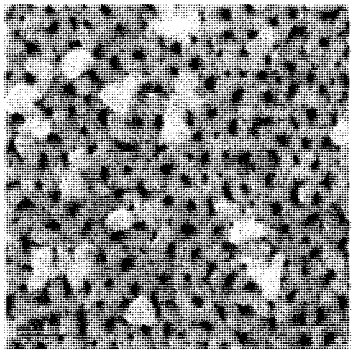
Nanopore Length Measurements for Center Point Reproducibility Run		
Object type	Result	Nanometers
Distance	2642	704.53
Distance	2626	700.27
Distance	2723	726.13
Distance	2559	682.40
Distance	2576	686.93
Distance	2458	655.47
Distance	2454	654.40
Distance	2597	692.53
Distance	2476	660.27
Distance	2497	665.87
Distance	2375	633.33
Distance	2430	648.00
Distance	2477	660.53
Distance	2305	614.67

Appendix M. $0^{o}C$ Substrate Data

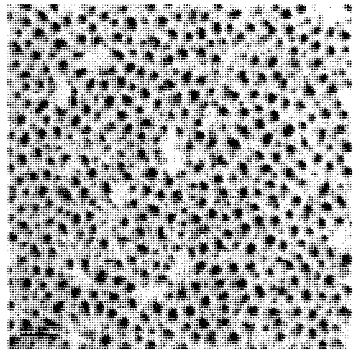
SEM Images for 0°C Substrate



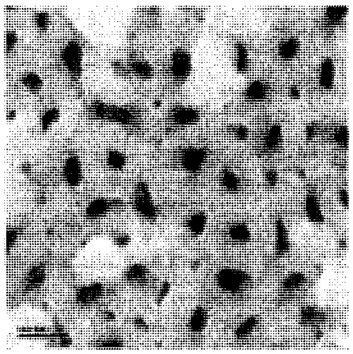
80 K
100 nm = 750 μm



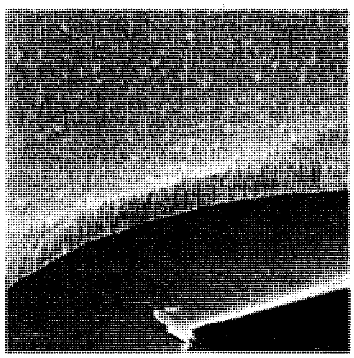
50 K
200 nm = 938 μm



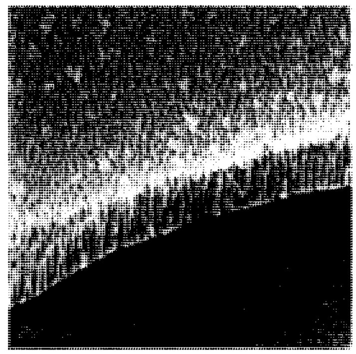
40 K
200 nm = 750 μm



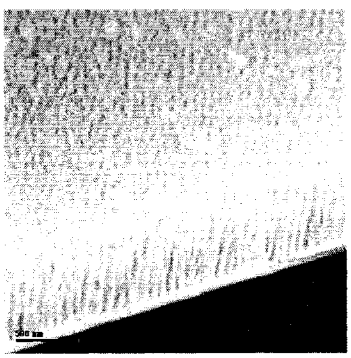
100 K
100 nm = 938 μm



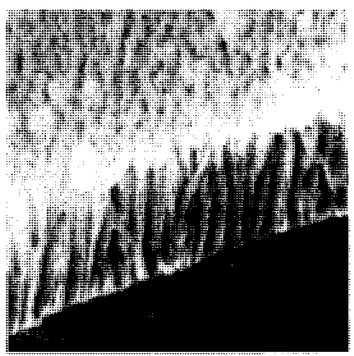
13 K
1 μm = 1025 μm



20 K
500 nm = 938 μm



25 K
500 nm = 1188 μm



45 K
200 nm = 850 μm

Diameter Measurements for 0° C Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	283	37.73	Diameter	273	36.40	Diameter	178	37.95
Diameter	270	36.00	Diameter	285	38.00	Diameter	147	31.34
Diameter	230	30.67	Diameter	313	41.73	Diameter	169	36.03
Diameter	273	36.40	Diameter	330	44.00	Diameter	158	33.69
Diameter	250	33.33	Diameter	344	45.87	Diameter	165	35.18
Diameter	284	37.87	Diameter	298	39.73	Diameter	208	44.35
Diameter	303	40.40	Diameter	299	39.87	Diameter	196	41.79
Diameter	292	38.93	Diameter	298	39.73	Diameter	138	29.42
Diameter	240	32.00	Diameter	288	38.40	Diameter	157	33.48
Diameter	311	41.47	Diameter	336	44.80	Diameter	165	35.18
Diameter	292	38.93	Diameter	359	47.87	Diameter	173	36.89
Diameter	272	36.27	Diameter	290	38.67	Diameter	211	44.99
Diameter	248	33.07	Diameter	303	40.40	Diameter	170	36.25
Diameter	267	35.60	Diameter	245	32.67	Diameter	171	36.46
Diameter	298	39.73	Diameter	266	35.47	Diameter	137	29.21
Diameter	251	33.47	Diameter	337	44.93	Diameter	149	31.77
Diameter	279	37.20	Diameter	249	33.20	Diameter	186	39.66
Diameter	241	32.13	Diameter	361	48.13	Diameter	232	49.47
Diameter	266	35.47	Diameter	307	40.93	Diameter	130	27.72
Diameter	269	35.87	Diameter	285	38.00	Diameter	179	38.17
Diameter	285	38.00	Diameter	326	43.47	Diameter	170	36.25
Diameter	311	41.47	Diameter	277	36.93	Diameter	180	38.38
Diameter	343	45.73	Diameter	313	41.73	Diameter	143	30.49
Diameter	308	41.07	Diameter	306	40.80	Diameter	178	37.95
Diameter	365	48.67	Diameter	284	37.87	Diameter	217	46.27
Diameter	258	34.40	Diameter	203	43.28	Diameter	160	34.12
Diameter	302	40.27	Diameter	193	41.15	Diameter	163	34.75
Diameter	259	34.53	Diameter	155	33.05	Diameter	163	34.75
Diameter	385	51.33	Diameter	194	41.36	Diameter	174	37.10
Diameter	332	44.27	Diameter	234	49.89	Diameter	144	30.70
Diameter	355	47.33	Diameter	154	32.84	Diameter	172	36.67
Diameter	299	39.87	Diameter	165	35.18	Diameter	197	42.00
Diameter	324	43.20	Diameter	163	34.75	Diameter	164	34.97
Diameter	325	43.33	Diameter	182	38.81	Diameter	196	41.79
Diameter	321	42.80	Diameter	156	33.26	Diameter	206	43.92
Diameter	280	37.33	Diameter	176	37.53	Diameter	183	39.02
Diameter	284	37.87	Diameter	200	42.64	Diameter	179	38.17
Diameter	319	42.53	Diameter	192	40.94	Diameter	221	47.12
Diameter	227	30.27	Diameter	189	40.30	Diameter	179	38.17
Diameter	293	39.07	Diameter	156	33.26	Diameter	203	43.28

Diameter Measurements for 0° C Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Diameter	178	37.95	Diameter	152	40.53	Diameter	174	18.55
Diameter	132	28.14	Diameter	170	45.33	Diameter	168	17.91
Diameter	163	34.75	Diameter	190	50.67	Diameter	185	19.72
Diameter	221	47.12	Diameter	155	41.33	Diameter	239	25.48
Diameter	219	46.70	Diameter	189	50.40	Diameter	308	32.84
Diameter	176	37.53	Diameter	144	38.40	Diameter	280	29.85
Diameter	172	36.67	Diameter	181	48.27	Diameter	235	25.05
Diameter	178	37.95	Diameter	161	42.93	Diameter	241	25.69
Diameter	204	43.50	Diameter	176	46.93	Diameter	321	34.22
Diameter	208	44.35	Diameter	183	48.80	Diameter	290	30.92
Diameter	164	43.73	Diameter	149	39.73	Diameter	214	22.81
Diameter	133	35.47	Diameter	160	42.67	Diameter	310	33.05
Diameter	144	38.40	Diameter	155	41.33	Diameter	309	32.94
Diameter	124	33.07	Diameter	159	42.40	Diameter	347	36.99
Diameter	169	45.07	Diameter	149	39.73	Diameter	204	21.75
Diameter	169	45.07	Diameter	158	42.13	Diameter	193	20.58
Diameter	150	40.00	Diameter	141	37.60	Diameter	231	24.63
Diameter	134	35.73	Diameter	171	45.60	Diameter	314	33.48
Diameter	137	36.53	Diameter	201	53.60	Diameter	356	37.95
Diameter	116	30.93	Diameter	168	44.80	Diameter	294	31.34
Diameter	151	40.27	Diameter	151	40.27	Diameter	292	31.13
Diameter	124	33.07	Diameter	191	50.93	Diameter	167	17.80
Diameter	113	30.13	Diameter	172	45.87	Diameter	244	26.01
Diameter	159	42.40	Diameter	165	44.00	Diameter	210	22.39
Diameter	162	43.20	Diameter	164	43.73	Diameter	290	30.92
Diameter	174	46.40	Diameter	166	44.27	Diameter	187	19.94
Diameter	179	47.73	Diameter	168	44.80	Diameter	218	23.24
Diameter	159	42.40	Diameter	158	42.13	Diameter	280	29.85
Diameter	128	34.13	Diameter	170	45.33	Diameter	281	29.96
Diameter	144	38.40	Diameter	164	43.73	Diameter	294	31.34
Diameter	187	49.87	Diameter	184	49.07	Diameter	192	20.47
Diameter	153	40.80	Diameter	151	40.27	Diameter	324	34.54
Diameter	167	44.53	Diameter	153	40.80	Diameter	280	29.85
Diameter	151	40.27	Diameter	149	39.73	Diameter	285	30.38
Diameter	160	42.67	Diameter	157	41.87	Diameter	353	37.63
Diameter	157	41.87	Diameter	249	26.55	Diameter	284	30.28
Diameter	178	47.47	Diameter	228	24.31	Diameter	334	35.61
Diameter	178	47.47	Diameter	242	25.80	Diameter	199	21.22
Diameter	133	35.47	Diameter	420	44.78	Diameter	344	36.67
Diameter	179	47.73	Diameter	317	33.80	Diameter	145	15.46

Nanopore Length Measurements for 0° C Run								
Object type	Result	Nanometers	Object type	Result	Nanometers	Object type	Result	Nanometers
Distance	539	525.85	Distance	963	513.33	Distance	1481	623.32
Distance	563	549.27	Distance	1023	545.31	Distance	1316	553.87
Distance	569	555.12	Distance	944	503.20	Distance	1312	552.19
Distance	565	551.22	Distance	1014	540.51	Distance	1365	574.49
Distance	532	519.02	Distance	968	515.99	Distance	1361	572.81
Distance	522	509.27	Distance	967	515.46	Distance	1368	575.76
Distance	540	526.83	Distance	961	512.26	Distance	1163	489.48
Distance	578	563.90	Distance	1046	557.57	Distance	1322	556.40
Distance	541	527.80	Distance	979	521.86	Distance	1371	577.02
Distance	564	550.24	Distance	1020	543.71	Distance	1356	570.71
Distance	551	537.56	Distance	1026	546.91	Distance	1238	521.04
Distance	547	533.66	Distance	1017	542.11	Distance	1372	577.44
Distance	539	525.85	Distance	955	509.06	Distance	1355	570.29
Distance	553	539.51	Distance	942	502.13	Distance	1335	561.87
Distance	553	539.51	Distance	960	511.73	Distance	1275	536.62
Distance	600	585.37	Distance	979	521.86	Distance	1805	759.68
Distance	526	513.17	Distance	941	501.60	Distance	1228	516.84
Distance	529	516.10	Distance	955	509.06	Distance	1354	569.87
Distance	518	505.37	Distance	940	501.07	Distance	1374	578.28
Distance	521	508.29	Distance	983	523.99	Distance	1318	554.71
Distance	514	501.46	Distance	993	529.32	Distance	1688	710.44
Distance	554	540.49	Distance	1010	538.38	Distance	2243	944.02
Distance	520	507.32	Distance	939	500.53	Distance	2091	880.05
Distance	514	501.46	Distance	951	506.93	Distance	2121	565.60
Distance	516	503.41	Distance	992	528.78	Distance	2200	586.67
Distance	547	533.66	Distance	955	509.06	Distance	2110	562.67
Distance	520	507.32	Distance	983	523.99	Distance	2097	559.20
Distance	609	594.15	Distance	1005	535.71	Distance	2079	554.40
Distance	526	513.17	Distance	973	518.66	Distance	1991	530.93
Distance	576	561.95	Distance	998	531.98	Distance	1791	477.60
Distance	653	637.07	Distance	971	517.59	Distance	2012	536.53
Distance	679	662.44	Distance	962	512.79	Distance	1971	525.60
Distance	532	519.02	Distance	1051	560.23	Distance	1996	532.27
Distance	517	504.39	Distance	938	500.00	Distance	1885	502.67
Distance	559	545.37	Distance	1663	699.92	Distance	1915	510.67
Distance	531	518.05	Distance	1564	658.25	Distance	1789	477.07
Distance	946	504.26	Distance	1526	642.26	Distance	1780	474.67
Distance	984	524.52	Distance	1550	652.36	Distance	1932	515.20
Distance	955	509.06	Distance	1475	620.79	Distance	1694	451.73
Distance	956	509.59	Distance	1510	635.52			